Seasonal Patterns of Forest Canopy and Their Relevance for the Global Carbon Cycle

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Declaration

I declare that this thesis has been composed by myself and has not been submitted in any previous application for a degree. The work described is my own except where stated otherwise.

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Abstract

In the terrestrial biosphere forests have a significant role as a carbon sink. Under recent climate change, it is increasingly important to detect seasonal change or 'phenology' that can influence the global carbon cycle. Monitoring canopies using camera systems has offered an inexpensive means to quantify the phenological changes. However, the reliability is not well known. In order to examine the usefulness of cameras to observe forest phenology, we analysed canopy images taken in two deciduous forests in Japan and England and investigate which colour index is best for tracking forest phenology and predict carbon uptake by trees. A camera test using model leaves under controlled conditions has also carried out to examine sensitivity of colour indices for discriminating leaf colours. The main findings of the present study are: 1) Time courses of colour indices derived from images taken in deciduous forests showed typical patterns throughout the growing season. Although cameras are not calibrated instrument, analysis of images allowed detecting the timings of phenological events such as leaf onset and leaf fall; 2) The strength of the green channel (or chromatic coordinate of green) was useful to observe leaf expansion as well as damage by spring late frost. However, the results of the camera test using model leaves suggested that this index was not sufficiently sensitive to detect leaf senescence. Amongst colour indices, Hue was the most robust metric for different cameras, different atmospheric conditions and different distances. The test also revealed Hue was useful to track nitrogen status of leaves; 3) Modelling results using a light use efficiency model for GPP showed a strong relationship between GPP and Hue, which was stronger than the relationships using alternative traditional indices.

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ε	Radiation conversion efficiency
I_{above}	Solar irradiance at above canopy
I_{below}	Solar irradiance at below canopy
k	Attenuation coefficient
k_{PAR}	Attenuation coefficient of PAR
N_{blue}	Digital number of blue
N_{green}	Digital number of green
N_{red}	Digital number of red
R_{blue}	Reflectance of blue band
R_{green}	Reflectance of green band
R_{red}	Reflectance of red band
S_{blue}	Strength of blue
S_{green}	Strength of green
S_{red}	Strength of red

List of Acronyms

ADFC	Automatic-capturing Digital Fisheye Camera
ANOVA	Analysis of variance
BBC	British Broadcasting Corporation
BES	British Ecological Society
DBH	Diameter at Breast Height
DOI	Digital Object Identifier
DOY	Day of Year
EC	Eddy Covariance
ECN	Environmental Change Network
EVI	Enhanced Vegetation Index
FPAR	Fraction of Absorbed Photosynthetically Active Radiation
FutMon	Forest Monitoring for the Future project
GBVI	Green Blue Vegetation Index

GEI	Green Excess Index
GPP	Gross Primary Productivity
GRVI	Green Red Vegetation Index
HSL	Hue, Saturation and Lightness
ICOS	European Commission Integrated Carbon Observing System
ICP Forests	International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests
IPG	The International Phenology Garden
MODIS	Moderate-Resolution Imaging Spectroradiometer
NDVI	Normalised Difference Vegetation Index
NTSC	National Television System Committee
ORNL DAAC	Oak Ridge National Laboratory Distributed Active Archive Center
PAI	Plant Area Index
PAR	Photosynthetically Active Radiation
PEN	Phenological Eyes Network
RBVI	Red Blue Vegetation Index
REI	Red Excess Index
RGB	Red, Green and Blue
ROI	Region Of Interest
USA-NPN	USA National Phenology Network

Chapter 1

Introduction

1 Introduction

There is much observational evidence to support the view of forests as a large global carbon sink (Pan *et al.* 2011). An important question is whether the sink strength will increase or diminish. Under recent climate change, the length of the growing season of trees in the boreal and temperate zone is an important variable that can influence the strength of the sink, by enhancing the duration of photosynthesis and thus increasing the annual carbon uptake (Piao *et al.* 2008). Thus the detection of phenological change is important, as the onset of growth in the spring and the timing of leaf abscission in the fall are key constraints on primary productivity, and they are not well represented in ecosystem models (Arora & Boer 2005). As well as exchanging carbon dioxide with the atmosphere through photosynthesis and respiration, forests exchange water and energy through evaporation. This also is determined by phenological changes, as the presence of leaves determines the surface conductance of the ecosystem whilst the surface roughness influences gas exchange and the albedo contributes to absorption of solar radiation. Forests respond to climate change, while at the same time, the response of forests may influence the change in climate through feedback processes. These feedbacks may involve soil (Cox *et al.* 2000; Cox *et al.* 2013), or changes in reflectance of vegetation (Bonan 2008), or changes in phenological and physiological processes which are not yet fully understand and which are not yet incorporated into vegetational models (Nichol *et al.* 2012). Thus it is crucial to investigate the seasonal change or phenological cycle of forests. In the past, this has mostly been undertaken at specific observation points known as phenological gardens. More recently it is being undertaken as an activity within a worldwide network of CO_2 eddy covariance flux stations (FLUXNET), whilst satellite imagery offers the spectral measurements to derive indices of vegetative state with a global spatial coverage at a resolution that varies from a few meters to kilometres or more. However, it is not easy to obtain reliable estimates of the effects on the carbon fluxes and phenological changes from satellite data because they are often manifest at small scale. For example abiotic/biotic stresses profoundly influence tree performance but may not be visible from space until they are widespread. Earth observation from satellite is often affected by clouds, and often the temporal resolution is insufficient to observe inter-annual differences in phenological events in relation to specific ground observations. Monitoring canopies using camera systems offers an inexpensive method of quantifying the phenological changes in great detail despite the limitations imposed by the camera systems themselves (they are not calibrated instruments like spectro-radiometers). Moreover, digital images themselves are often influenced by illumination conditions and the reliability of camera systems for canopy surveillance is not well known.

1.1 Monitoring seasonal change in forests

Phenology is the study of the timing of life-cycle events, especially as influenced by the seasons and by the changes in weather patterns from year to year. To observe plant phenology and to relate it to growth and photosynthesis, three major methods have been applied: traditional observation networks to monitor specific events of species, carbon flux monitoring by eddy-covariance and vegetation monitoring using satellite remote sensing devices.

1.1.1 Recording phenology: Species-level phenology

In Kyoto, Japan, dates of cherry flowering at the Royal Court were recorded from A.D. 794 to 1868 (Aono & Kazui 2008). An English naturalist, Robert Marsham started to record the indications of spring in Norfolk, England in 1736 and his family maintained these records until the 1950s (Sparks & Carey 1995). The International Phenology Garden (IPG) was founded in 1957 to obtain comparable phenological data across Europe by observing genetically identical plants or clones (Menzel 2000). Historically, phenological observations have been conducted by amateur naturalists and the reliability was often dependent on the skills and effort of the observer. IPG has published manuals and annual observations in the journal of IPGs, the *Arboreta Phaenologica*, employing standardised protocols reduced inaccuracy of the observations. The continuing observations in about 50 gardens for 23 plant species through different climate regions in Europe have been analysed comprehensively to contribute to the study of recent global climate change (Menzel 2000). Phenology is also observed at ICP Forests (the International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests) launched in 1985 for comprehensive data gathering on forest condition in Europe (Menzel 2000). Intensive monitoring including soil chemistry, foliar nutrients, annual woody increments, meteorological conditions, ground vegetation, deposition of air pollutants, has been carried out at the 800 second level (Level II) plots since 1994 in selected forest ecosystems, while recording of phenological phases was added in 1999. The requirement to record phenology on local-to-continental scales contributed to the establishments of The Global Phenological Monitoring (GPM) program in 1998 and the USA National Phenology Network (USA-NPN) and associated regional networks (Wingate *et al.* 2008; Morisette *et al.* 2009; Richardson *et al.* 2009). In Europe, the dates for leafing and flowering advanced 2.5 days per decade, whereas the changes for leaf colouring and fall were ambiguous (Menzel *et al.* 2006). However, this traditional observation method is labour intensive and the quality depends on observers.

1.1.2 Atmospheric monitoring networks: Monitoring carbon dynamics

Atmospheric monitoring of carbon dioxide concentration provides an indirect technique to study phenology as an indication of the timing of carbon uptake through photosynthesis. At a global scale, Keeling established a CO_2 observatory at Mauna Loa in Hawaii in the 1950s and first demonstrated that in the upward trend in the CO_2 concentration there was a substantial annual cycle, whereby the concentration decreased during summer in the Northern Hemisphere and increased in the winter (Keeling, Chin & Whorf 1996). The summer decline is attributable to the strong summertime uptake by photosynthesis of terrestrial vegetation. This is in agreement with the idea that warmer temperatures promote increases in plant growth and carbon fixation in the summer. At an ecosystem scale, eddy-covariance flux towers continuously measure CO_2 concentrations in upward- and downward-moving air components and the data can be used to separate carbon fluxes into uptake through photosynthesis and release through respiration. Started in the early 1990s, the global network of eddy covariance sites (FLUXNET) now monitors the fluxes associated with regional networks such as CARBOEUROFLUX, AmeriFlux, AsiaFlux and OzNet, providing opportunities to investigate relationships between canopy phenology and ecosystem physiology at a fine temporal scale. However, the system is expensive in terms of equipment and skilled maintenance, and the locations are limited by the requirement for flat sites and homogeneity of land cover (Baldocchi 2003).

1.1.3 Remote sensing: Scalable phenology observation

Satellite observations of terrestrial ecosystems attempt to determine the distribution and the change in vegetation for a long period (decades) and at a global scale. In early 1970s, 'Green Wave' (vernal green up) and 'Brown Wave' (autumnal browning) in temperate vegetation was observed in the band ratio parameter calculated from reflection of red and infrared regions by the multispectral scanner (MSS) on Landsat (Knapp & Dethier 1976). The efforts have carried on using thematic mapper sensors on Landsat and the Advanced Very High Resolution Radiometer (AVHRR) of the National Oceanic and Atmospheric Administration (NOAA) since the 1980s and the newer generation of sensors such as the Vegetation sensor on Systéme Probatoire pour l'Observation de la Terre (SPOT) whilst the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra and Aqua have provided frequent observations (Table 1.1; Reed, Schwartz & Xiao 2009). To exploit the spectral contrast between the red region which is strongly absorbed by live vegetation and the green region which is strongly reflected by live vegetation, several vegetation indices have been suggested. In particular, the Normalised Difference Vegetation Index (NDVI; Tucker 1979) and the Enhanced Vegetation Index (EVI; Huete *et al.* 2002) are commonly used in research and in publicly available products. However, there are disadvantages to this approach, too: long time-series of data are hard to acquire because of the limited life span of a satellite borne sensor; in addition, data are not collected when the landscape is cloud-covered. In some respects it is an advantage that the satellite 'sees' a large amount of landscape (spatial resolution is from a few square metres to many square km), as a large sample integrates over many thousands of plants, but the species mixture is uncontrolled.

Table 1.1 Satellite sensors and data sets utilised for land surface phenology studies (Reed, Schwartz & Xiao 2009)

Satellite	Sensor	Operation	Resolution	Frequency
Landsat	MSS	1973–1985	79 m	18 days
Landsat	TM	1984–present	30 m	16 days
Landsat	ETM+	1999–present	30 m	16 days
NOAA	AVHRR	1982–present	8 km	twice monthly
NOAA	AVHRR	1989–present	1 km	biweekly
SPOT	Vegetation	1999–present	1 km	1–2 days
Terra	MODIS	2000–present	250 m, 500 m, 1 km	1–2 days
Aqua	MODIS	2002–present	250 m, 500 m, 1 km	1–2 days
Envisat	MERIS	2002–present	300 m	1–3 days

1.2 Forest observation using camera systems

Fifty years ago hemispherical photographs were introduced to observe canopies and to estimate the amount of leaves by analysis of the gap fraction (Anderson 1964). Recent advances in camera technology and the interpretation of digital imagery now allow the quantification of plant canopy development at flux sites automatically and without the inherent subjectivity of observer-based systems (Richardson *et al.* 2007). As "near-surface" remote sensing, networks of digital cameras dedicated to phenological observations have expanded rapidly to monitor diverse ecosystems worldwide (Wingate *et al.* 2008; Morisette *et al.* 2009).

1.2.1 Use of cameras to observe forest phenology

Responding to a suggestion to install video cameras to record the state of the canopy at eddy covariance sites (Baldocchi *et al.* 2005), Richardson *et al*. (2007) set up a standard, commercial webcam in the Bartlett Experimental Forest, USA, and demonstrated that the quantitative analysis using RGB (Red, Green and Blue) digital numbers extracted from the recorded images was useful for tracking both spring canopy development and autumn senescence in this deciduous broadleaf forest (Richardson *et al.* 2007; Richardson *et al.* 2009). They found normalising the brightness reduced day-by-day variability. Fitting a logistic curve to the time series of relative green brightness was helpful in identifying the dates for onset of budbreak and the fall of leaves, as well as the peak of relative red brightness to indicate the timing of autumn colouring. However, the timing and rate varied across the canopy area and the distance from the camera. The variability in autumn was greater than in spring. A similar analysis was successfully applied to phenological observations at several European flux sites for two mixed forests and the phenological dates for individual trees were calculated mathematically using first and second derivatives (Ahrends *et al.* 2008; Ahrends *et al.* 2009). The dates of onset were similar to those by visual assessment, while the dates for starting senescence and the dates of leaffall strongly varied (the maximum error was 33 days). Moreover, the sign of the error was different for different species. Although the previous studies suggested the huge potential of using cameras for observing phenology, at the same time the difficulty of establishing an automatic global observing system has been highlighted. .

The trends of green brightness were compared with the seasonal patterns of CO_2 exchange as measured by eddy covariance methods (Ahrends *et al.* 2009; Richardson *et al.* 2009). Although the timing for the onset of green signals coincided with the timing for the onset of photosynthetic productivity, the increase of photosynthesis was slower and the peak of photosynthetic delayed the increase of green signals. The peak of green seems to indicate the peak of leaf expansion, while development of full photosynthetic capacity occurred some time after leaf expansion (Morecroft, Stokes & Morison 2003). There might be a better signal in canopy images to estimate photosynthetic rate. More investigation is needed to assess the relationship between forest colour and carbon uptake.

It is interesting to note that there are now many thousands of outdoor cameras in use, for various purposes such as surveillance, tourism promotion and wildlife conservation. Although many different types of camera are being used in these activities, the results of colour analysis may be useful in determining the length of the growing season for various types of vegetation that happen to be part of the image's content. Such images could be used as a reference to '*ground truth*' information derived from satellite observation at a large spatial scale (Jacobs *et al.* 2009; Graham *et al.* 2010; Ide & Oguma 2010). However, image analysis has not been standardised yet and it is unclear which colour indices are most suitable for comparison with vegetation indices derived from spectral measurements.

1.2.2 Camera sensors and image processing

Digital cameras detect the intensity of incoming radiation (light) using image sensors sensitive to red, green and blue and store signals in a standard format file as the digital numbers of the three channels for each pixel. Figure 1.1 shows how digital cameras convert captured light into an image. Light reflected from the subject is captured and focused by the lens. For a conventional digital camera, the lens assembly includes an infrared (IR) blocking filter. Therefore, only the visible range of light reaches the imaging sensor which can be a CCD (Charge Coupled Device) or a CMOS (Complementary Metal-Oxide Semiconductor). Since a conventional CCD/CMOS sensor detects only a shade of grey, a colour filter matrix is placed in front of each sensor pixel. A common filter is the Bayer Filter which has a particular pattern of red, green and blue (Bayer 1976). The green filters outnumber the blue or red, so that the sampling rate of three colours matches the human visual system (which is more sensitive to green). The analogue signal of light detected by the sensor is amplified and converted to digital form. Then, a de-mosaicing process interpolates missing pixels of each channel and makes the full colour grid of pixels. Several imaging processes follow including white balancing, colour correction and sharpening in order to improve image quality. Finally, the image data is compressed, formatted and stored into a storage device such as a memory card. Through the processes, the original radiative information is manipulated and lost for compression. However, both the exact sensor sensitivity and the detailed algorithms for image processing are never disclosed by the manufacturer. Therefore, some researchers are sceptical about quantitative use of digital images, pointing to their inferiority compared to properly calibrated radiometric measurements.

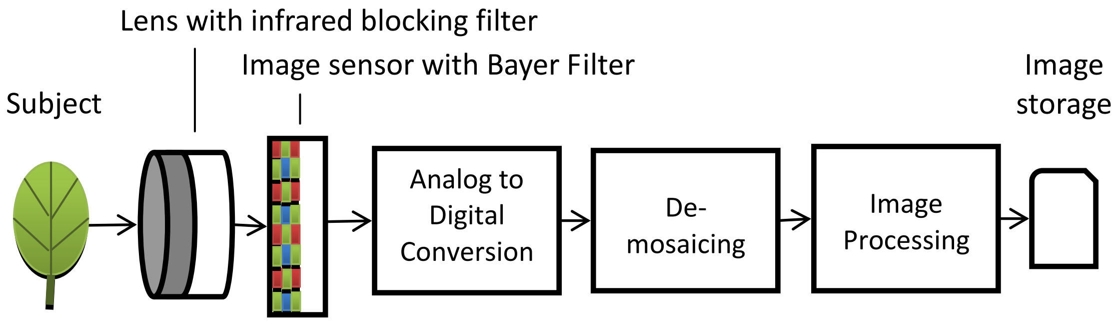

Figure 1.1 Processes that reflected light converts into images in digital cameras.

1.2.3 Colour coordinate systems and the colour index

The colour coordinate system which describes colours using three dimensions, red, green and blue, is called the RGB colour system (Figure 1.2a). A variety of colour indices for tracking canopy phenology have been suggested using RGB digital numbers extracted from canopy images. For example, chromatic co-ordinates of green (Gillespie, Kahle & Walker 1987), which come from the strength of green relative to the total of the three channels has been used to determine foliage phenology (e.g., Ahrends *et al.* 2008), while some studies showed that the Green Excess Index (Woebbecke *et al.* 1995) could also be useful (e.g., Richardson *et al.* 2009). Others have devised colour indices analogous to the familiar Normalised Difference Vegetation Index (NDVI) retrieved from satellite spectral data, such as the normalised difference between red and blue for weather filtering (Ide & Oguma 2010). However, such indices often vary with camera type, camera setting and light conditions, and it is not straightforward to find the best indices for canopy observations.

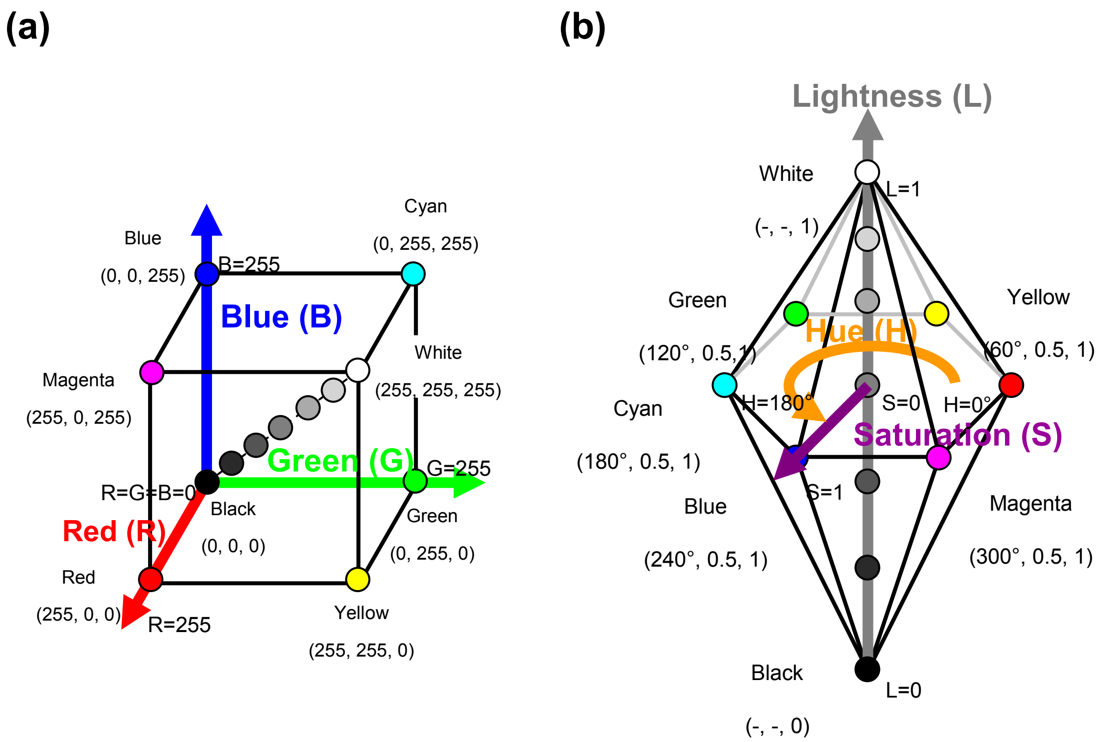

Figure 1.2 Schematic diagrams of colour spaces used in the present study. Red, Green, Blue (RGB) colour system (a) and Hue, Saturation, Lightness (HSL) colour system (b). For RGB, system of coodinates is x, y, z, where x is red value, y is green value and z is blue value. For HSL, system of coodinates is x, y, z, where x is hue, y is saturation and z is lightness (CG-ARTS 2004).

Meanwhile, Graham *et al*. (2009) measured budburst and leaf area expansion of *Rhododendron* using a mobile camera system and reported the advantages of the use of Hue, Saturation and Lightness (HSL) colour system derived by Smith (1978). Graham's work was important because it went beyond indices that were merely analogous to those used in remote sensing, and instead adopted the paradigms of colour technology. In this thesis I try to take this approach further and to relate colour indices to the carbon cycle. The concept describes colour by its tone, intensity and brightness in three-dimensional space (Figure 1.2b). The separation of

Hue from Saturation and Lightness reduces the influence of illumination conditions on hue and thus helps to deal with colour in images containing both sunlit and shaded regions (Liu & Moore 1990). Although the RGB colour system is native for digital images, the HSL colour system appears to have some potential to examine canopy images.

1.2.4 Camera network and camera system

A FLUXNET survey (Wingate *et al.* 2008) revealed that at least 26 cameras have been used to observe canopy phenology at flux sites (Figure 1.3).

Figure 1.3 Global distribution of flux sites with camera systems (Wingate *et al.* 2008)

In North America, the PhenoCam network, which began at Bartlett Forest (Richardson *et al.* 2007) has rapidly expanded to include more than 75 core sites enabling continental-scale phenological observation (PhenoCam 2013). In Asia, Maeda & Gamo (2004) have patented a system using the separate RGB indices of a video system called 'Gamo's Eye' at the JapanFlux' Takayama Site. In collaboration with AsiaFlux, the Phenological Eyes Network (PEN) has formed a network of ground observatories using three types of optical instrument: cameras, spectro-radiometers and sunphotometers (Tsuchida *et al.* 2005; Nishida 2007). A similar network has recently grown in Europe and a synthetic study has been conducted for 26 cameras in deciduous forests, evergreen forests, grasslands and croplands (Figure 1.4, Wingate *et al.* in preparation).

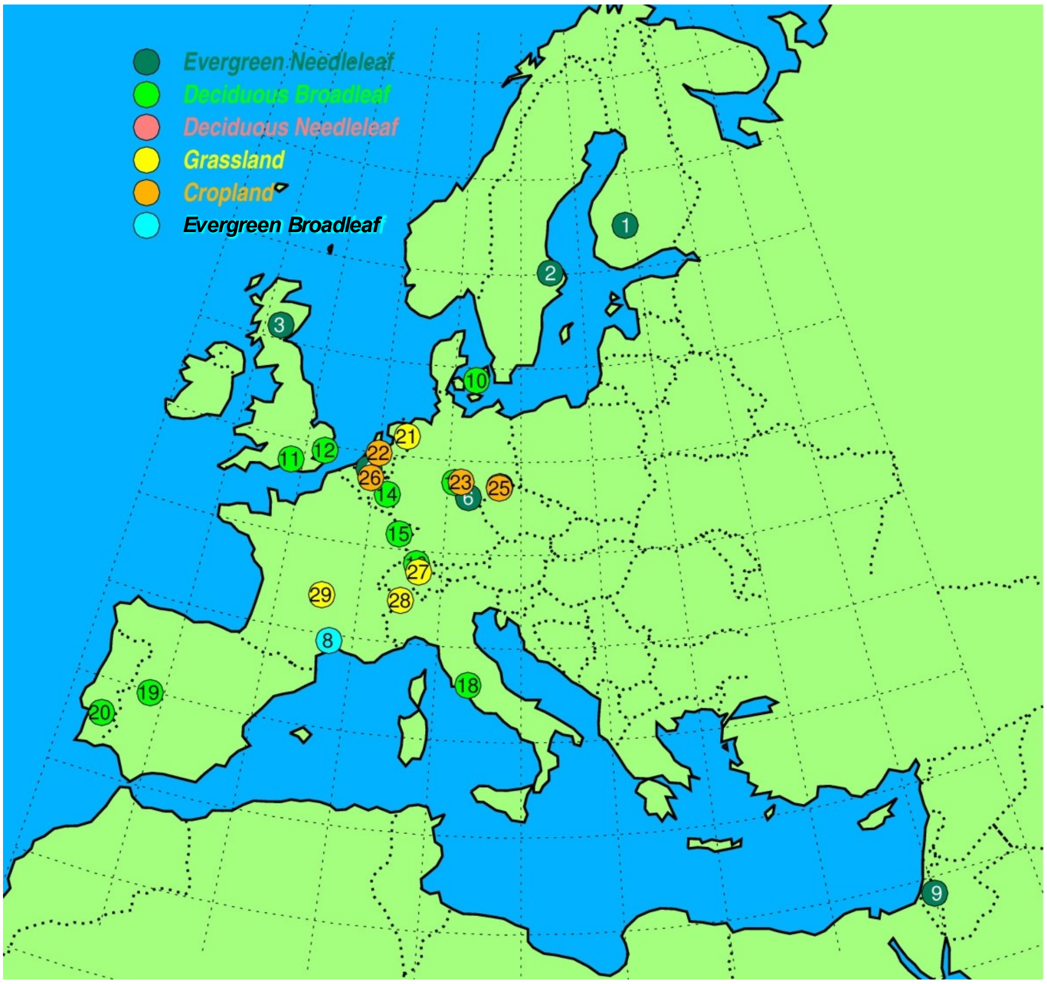

Figure 1.4 Distribution of camera systems at flux sites in Europe (Wingate *et al.* in preparation).

The PhenoCam network proposed a standard protocol using a type of networked surveillance camera with a setting guide, while the Phenological Eyes Network developed the original camera system based on a commercial digital camera with a fish-eye lens for observations at AsiaFlux sites. Meanwhile European sites have used a range of cameras, although the networked cameras proposed by PhenoCam Net have been most widely deployed. Phenological observation using camera systems is still on a '*learning curve*'. Establishing a global standard protocol is highly desirable and to do it, more *in situ* and experimental tests are necessary. In this thesis, I have tried to contribute to this goal.

1.3 Aim and structure of thesis

The primary objective of this study is to investigate the seasonal patterns of forest canopies using digital camera images as a tool for phenology monitoring in forest ecosystems. Camera systems are available with a cost of 100-150 GBP, which is below one tenth part of a portable spectro-radiometer. The expectations of the inexpensive method are high. Deciduous broad-leaved forests show obvious visual transitions through a year, which can be detected by camera images. The seasonal changes in the images may also correlate with changes in carbon flux. Digital images may also capture changes in tree physiology such as leaf pigments. The key research questions are:

(i) Can digital images detect phenological events in deciduous trees?

(ii) What is the optimal colour index for recording canopy phenology?

(iii) Do changes in digital images relate to changes in CO_2 fluxes in deciduous canopies?

Three of the chapters are written in the style of papers for submission to scientific journals, which are referred to as Paper I, II and III. These are followed by, a chapter with general discussion and conclusions. Appendices contain some information about public outreach of the work through the media.

Chapter 2

Paper I - The comparison of several colour indices for the photographic recording of canopy phenology of *Fagus crenata* Blume in eastern Japan

Which colour index is useful to track phenology of deciduous species in a temperate region? Digital images of a deciduous forest in Japan taken in 2008 were analysed to investigate the seasonal change in colour. A variety of colour indices were calculated using RGB values extracted from images.

Chapter 3

Paper II - The relationship between carbon dioxide uptake and canopy colour from two camera systems in a deciduous forest in southern England

Can forest colour tell how much carbon trees absorb? Two different camera systems were installed in a deciduous forest in southern England on top of a tower for the measurement of carbon flux using the Eddy Covariance method. We compared the GPP measured using the Eddy Covariance system with the GPP estimated using a Light Use Efficiency model replacing the parameter of fraction of absorbed photosynthetically active radiation (FPAR) with the colour indices suggested by **Paper I**.

Chapter 4

Paper III - Sensitivity of colour indices for discriminating leaf colours from digital photographs

Which colour index is robust between different cameras and different illuminations and which colour index is sensitive to discriminate leaf colours? In order to ensure the advantages of our colour indices in **Paper I** and **Paper II**, we carried out camera experiments under controlled conditions using a set of standard colour charts to represent model leaves with different stages.

Chapter 5

General Discussion, Conclusions and Recommendations

The findings presented in the papers above are reviewed and a discussion is presented regarding the use of camera systems to monitor forest phenology, together with an analysis of some issues that have emerged and suggestions for further research.

Appendix

The installation of one of the cameras in Alice Holt was supported by a grant from the UK–Japan 2008 Collaborative Project Grant Award of the British Embassy, Tokyo, and the British Council to commemorate the 150th anniversary of official diplomatic relations between Japan and the UK. The collaborative project is introduced in this chapter. The author was invited to co-author a chapter in a book titled '*Forest Monitoring: Methods for terrestrial investigations in Europe with an overview of North America and Asia*'. The appendix includes a copy of the chapter '*Tree Phenology*' as well as some media coverage for the present study. At the end, preliminary analyses using the latest images from Alice Holt (obtained after **Paper II** was published) have been appended.

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Chapter 2

Paper I: The comparison of several colour indices for the photographic recording of canopy phenology of *Fagus crenata* Blume in eastern Japan

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2 Paper I: Comparision of colour indices of *Fagus* images

2.1 Abstract

Background: To understand how forests and woodland respond to global climate change, phenological observations are being made at a number of sites worldwide. Recently, digital cameras have been deployed as part of the existing network of ecosystem CO_2 flux towers to provide a time-series of canopy images, and various numerical indices have so far been used by different authors.

Aims: To identify which are the most effective colour indices to calculate from the signals extracted from digital cameras, in order to provide recommendations to the scientific community.

Methods: Sample images of a Japanese beech (*Fagus crenata*) forest on Mt. Tsukuba (Japan) were used to define and calculate 12 colour signals and vegetation indices.

Results: Although the strength of green signal and green excess index were reliable indicators for estimating foliage growth period, the indices were susceptible to low-visibility weather conditions and distance from the camera. Hue provided a robust metric, showing much less scatter during the vegetative period and a good indication of spring bud break. The bud break dates derived from the indices were slightly earlier than those assessed by visual observation, while the abscission dates were later.

Conclusions: We propose that of all the candidate colour indices, hue is the most promising for the detection of bud break as it was least affected by atmospheric conditions.

Key words: canopy phenology; deciduous broadleaved forest; digital image; HSL; RGB

2.2 Introduction

To understand how vegetation responds to climate warming, remote surveillance techniques have been established to record continuously the long-term patterns of phenology, including bud break, flowering and leaf abscission, and relate these phenological events to the physiological activity of the canopy (Richardson *et al.* 2007; Wingate *et al.* 2008; Morisette *et al.* 2009). Ultimately, we expect this will be achieved by using satellites; however complementary 'ground truth' approaches such as citizen-based observations (e.g. the GLOBE programme in the UK, http://www.globe.org.uk) or digital camera networks (Wingate *et al.* 2008; Jacobs *et al.* 2009; Graham *et al.* 2010) are also essential to verify phenological patterns. Recently, there have been attempts to analyse the colour signals, red, green and blue (RGB), obtained from commercially available digital camera images across many different ecosystems (Richardson *et al.* 2007; Ahrends *et al.* 2008; Maeda *et al.* 2008; Ahrends *et al.* 2009; Jacobs *et al.* 2009; Richardson *et al.* 2009; Graham *et al.* 2010; Ide & Oguma 2010). So far, there is no consensus on how these signals should be combined to resolve adequately the key phenological events, such as bud break and leaf abscission. There are many possible indices based on the RGB signals. (Maeda & Gamo 2004) have patented a system that uses separate RGB indices in a video system. Green fraction is sometimes used to detect foliage phenology (e.g. Ahrends *et al.* 2008, 2009), while red fraction has an advantage to detect autumn colouration (Richardson *et al.* 2009). Others meanwhile have devised vegetation indices analogous to the familiar Normalised Difference Vegetation Index (NDVI) retrieved from satellite spectral data. Normalised difference between red and blue, which has a good correlation with the chlorophyll content of crop plants (Kawashima & Nakatani 1998), has been used as a weather filter of outdoor images (Ide & Oguma 2010). The seasonal pattern in green excess index (GEI) was correlated with data of gross primary productivity of a forest (Richardson *et al.* 2009). Of particular interest is the attempt to use the HSL (Hue, Saturation, Lightness) colour system as the basis of an alternative index. The HSL concept of describing colour by its intensity and brightness in three-dimensional space was devised by (Smith 1978) as an early contribution to computer graphics, and is said to be similar to the colour-recognition system of the human eye. Previously, the HSL system has been applied to phenological research to process spectral data (Kodani *et al.* 2002), but more recently Graham *et al.* (2009) used it to detect bud break and measure leaf area expansion in *Rhododendron occidentale* Torr. & A. Gray. Using viewpoints within the canopy, Graham *et al.* (2009) found the hue-based colour system to be more useful than the RGB colour system for their site.

However, more tests are now required to evaluate the applicability of these diverse approaches, and to assess which of them is best related to phenological processes and ideally to the seasonal cycle of forest CO_2 fluxes. We present a detailed study of a particular case, using a number of indices obtained from a time-series of images. We ask the general question: what is the best way to represent colour signals as an index? We examine recent data of *Fagus crenata* Blume from a case study in a temperate forest in Japan, collected by the Phenological Eyes Network (PEN, http://www.pheno-eye.org/ index_e.html; Tsuchida *et al.* 2005; Nishida 2007).

2.3 Materials and Methods

2.3.1 Site

Mt. Tsukuba is located 20 km north-east of Tsukuba city, Japan. A meteorological observation station was installed in January 2006 on the top of the west peak of Mt. Tsukuba (36°13’ 30’’ N, 140°5’ 52.8’’ E, 868 m above sea level) by the University of Tsukuba (Hayashi & Project 2006). From 2007 onwards, a digital camera was mounted on a rooftop terrace by the PEN to observe the seasonal change of adjacent trees. The mountain is covered by mixed forests of Japanese beech (*Fagus crenata*), Japanese mountain maple (*Acer palmatum* Thunberg) and a variety of conifers such as Japanese cedar (*Cryptomeria japonica* D. Don) and Japanese red pine (*Pinus densiflora* Siebold et Zucc). In 2008, the mean annual temperature was 9.9 °C, the mean temperature in August was 20.5 °C and the annual precipitation was 1382 mm; the annual mean temperature and the annual amount of precipitation were within the normal range, with low rainfall in July and heavy rain in August.

2.3.2 Digital camera images

A commercially available compact digital camera (Coolpix 4500, 4.0 million pixels, Nikon Corp., Japan) was installed within a waterproof housing at 12 m height, pointing toward north-west, using the camera's original lens (focal length 7.85–32 mm) according to the protocol of PEN (Tsuchida *et al*. 2005, Nishida 2007), and focusing on a target *F. crenata* tree in a dense forest on the western slope of Mt. Tsukuba. Canopy images of the same scene were taken at 12:00 local time and stored as a compressed JPEG file (resolution 2272 × 1704 pixels, three channels of 8-bit RGB colour information, and 'fine' image quality by the setting of camera). Images were captured in automatic aperture and exposure mode and white balance was fixed to 'cloudy'. This study was based on the images captured in 2008. Images for the periods from Day-of-Year (DOY) 63 to 96, from DOY 210 to 219 and from DOY 362 to 366 were missing due to system failure. A total of 315 days of images were incorporated in our analysis.

2.3.3 Image analysis

A customised MATLAB program (7.7.0, R2008b; The MathWorks) developed by AD Richardson and JP Jenkins (cf. Richardson *et al.* 2007) was modified to process the image files. Sample images and the region of interest (ROI) used for this analysis are shown in Figure 2.1. The ROI was set to three separate regions: (1) a prominent large beech tree, well in focus; (2) a beech canopy to the left and behind the main tree; and (3) a distant beech tree near the boundary of the forest and the sky (Figure 2.1). Images were classified into three groups determined by weather conditions; (1) images under high solar radiation conditions; (2) images under low solar radiation conditions; and (3) low-visibility images corresponding to days with haze and rain drops on the window of the water-proof housing. Kawashima and Nakatani (1998) reported different distribution patterns in frequency of pixel values between images taken on a clear day and those taken on a cloudy day. Although other studies often excluded low-visibility images, we analysed them to examine the sensitivity of colour indices to wet conditions. Images taken during high and low solar radiation conditions were identified using the data of downward shortwave radiation measured every 10 min (EKO/Photo diode). A threshold of 833.3Wm^{-2} (0.5 MJm^{-2} per 10 min) was used to separate high-radiation days from low-radiation days. Low-visibility images were identified 'by eye'.

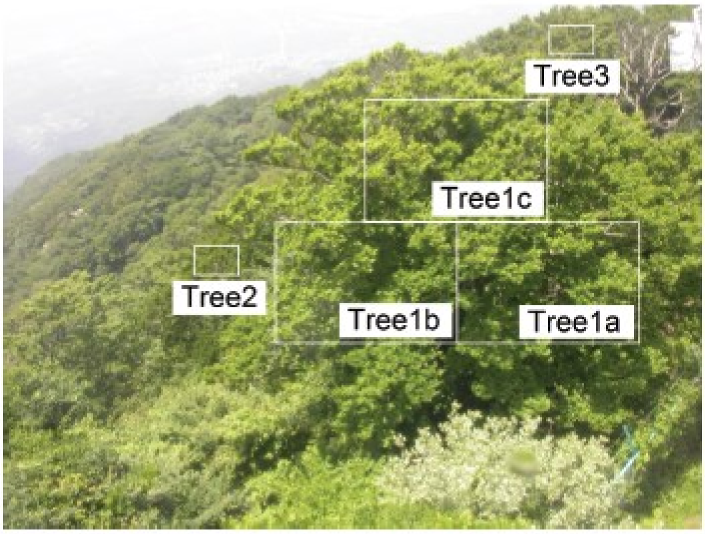

Figure 2.1 Example image (DOY = 176). The white squares on the image indicate the regions of interest. The camera was pointing north-west, and the overall field of view contains about 1 ha of forest. The foreground is about 20 m away.

Information from the 8-bit colour digital images consisted of three values, each a digital number between 0 and 255, representing red, green and blue. We extracted RGB values for each pixel of each image, from which the mean of all pixel values for a given ROI was calculated. A number of indices (equations are listed in Table 2.1) were calculated to explore the suitability of each index for observing changes in canopy phenology. This list of indices is not exhaustive, but it includes those indices which have been debated at recent phenology meetings. The relative strength of the signals in each channel was expressed as the ratio of the values of each colour relative to the total values of all three colours. In order to compare different colour systems, the values of the RGB channels were converted into hue, saturation, and lightness for the HSL colour system (Joblove & Greenberg 1978) and monochrome luminance following the National Television System Committee (NTSC) standard (SMPTE 2004). RGB and HSL colour spaces used are explained diagrammatically in Figure 2.S1 of the supplementary materials.

Table 2.1 Definitions of the signals and the derived vegetation indices from the digital camera images. See also Figure 2.S1 in 2.9.

Signals and indices	Formulation		References
Strength of signal in RGB channel	$S_{channel} = n_{channel} / (n_{red} + n_{green} + n_{blue})$		Richardson *et al.*(2007)
HSL signals (Double hexagonal pyramid model)			Takagi & Shimoda (1995), Joblove & Greenberg (1978)
Hue	$Hue = (b - r) / ((I_{max} - I_{min}) \times 60) + 120$	if $g = I_{max}$	
	$Hue = (r - g) / ((I_{max} - I_{min}) \times 60) + 240$	if $b = I_{max}$	
	$Hue = (g - b) / ((I_{max} - I_{min}) \times 60) + 360$	else if $g < b$	
	$Hue = (g - b) / ((I_{max} - I_{min}) \times 60)$	otherwise	
Lightness	$L = (I_{max} + I_{min}) / 2$		
Saturation	$S = (I_{max} - I_{min}) / (I_{max} + I_{min})$	if $L \leq 0.5$	
	$S = (I_{max} - I_{min}) / (2 - (I_{max} + I_{min}))$	if $L > 0.5$	
	$S = 0$	if $I_{max} = I_{min}$	
Monochrome luminance	$M_l = 0.2989r + 0.5870g + 0.1140 b)$		SMPTE (2004)
Vegetation indices			
Green Excess Index	$GEI = 2 \times n_{green} / (n_{red} + n_{blue})$		Woebbecke *et al.* (1995)*, Richardson *et al.*(2007)
Red Excess Index	$REI = 1.4n_{red} - n_{green}$		Meyer & Neto (2008)
Green Red Vegetation index	$GRVI = (n_{green} - n_{red})/ (n_{green} + n_{red})$		Falkowski *et al.* (2005), Kawashima & Nakatani (1998)
Green Blue Vegetation index	$GBVI = (n_{green} - n_{blue})/ (n_{green} + n_{blue})$		Kawashima & Nakatani (1998)
Red Blue Vegetation index	$RBVI = (n_{red} - n_{blue})/ (n_{red} + n_{blue})$		Kawashima & Nakatani (1998)

Note: n_{red}, n_{green}, n_{blue} are the values of red, green and blue respectively and nchannel is one of these; $r = n_{red} / 255$, $g = n_{green} / 255$, $b = n_{blue} / 255$; I_{max} is maximum value of r, g and b and I_{min} is minimum value of r, g and b.
∗Cited in Meyer & Neto (2008).

Classical observations of phenology made by human observers are normally used to define particular phenological phases (e.g. data from the International Phenological Gardens in Europe). We compared the various dates of phenological events obtained from visual inspection and from the indices obtained from the digital camera images.

To compare the seasonal patterns of indices between the different regions of interest, we excluded the data of low-visibility images and calculated the 5-day running averages. The dates of bud break and abscission were estimated by detecting an abrupt increase or decrease in the indices. Individual images were observed by eye; the day on which leaves first appeared in each ROI was defined as the day of bud break, and the day all leaves disappeared in each ROI was defined as the day of abscission (sample images are shown in Figure 2.S2 in 2.9). The dates for the indices were manually determined by reading graphs; the day that the trend started to change from winter state was used for the bud break estimation, and the day that the trend returned to the winter state was used for the abscission. Most indices showed a peak or trough in spring and autumn, with some deviation from the dates of bud break and abscission. We estimated peaks of spring and autumn for each index using maximum or minimum values of the running average data.

2.4 Results

2.4.1 Seasonal pattern of RGB values and indices

We first report the basic data from the regions of interest delineated in Figure 2.1. The red, green, and blue values extracted from image files for a region of the dominant beech tree are shown in Figure 2.2. Both red and blue values decreased sharply when leaf-flushing started. Thereafter the red values stabilised over the summer period until a dramatic increase associated with autumn leaf colouration was observed. The blue values increased slightly during midsummer but declined again in autumn. In contrast, the green values remained comparatively constant throughout the year, with the exception of a slight decrease detected in autumn. The values for low-visibility images showed greater dispersion; in particular, the blue values were susceptible to atmospheric visibility in the foliage period.

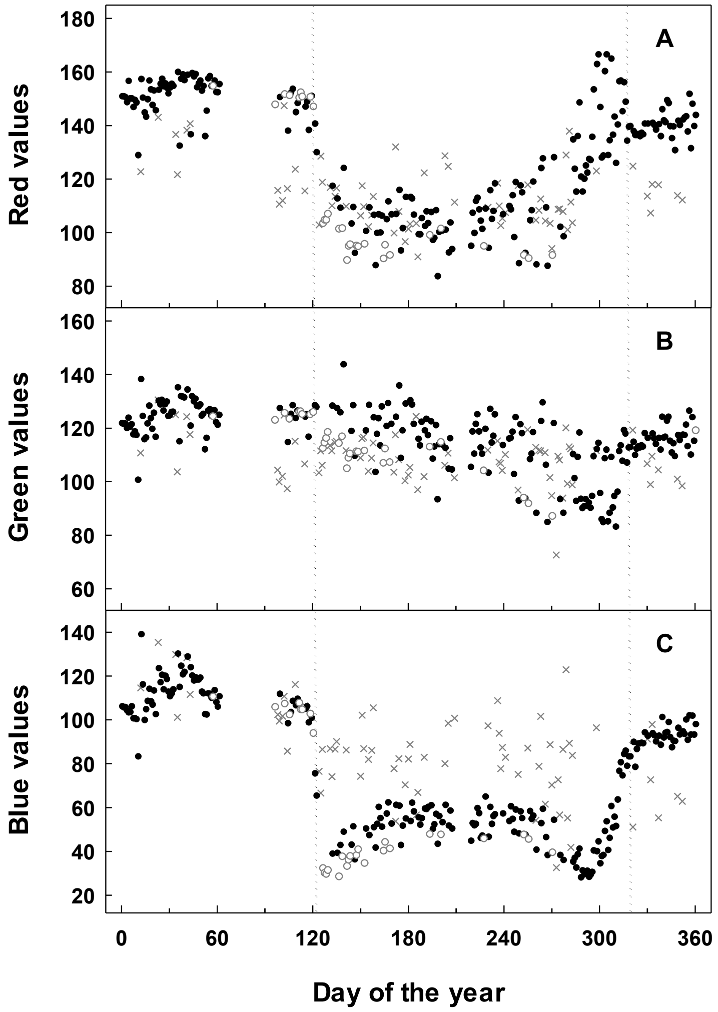

Figure 2.2 Red, green and blue (RGB) values extracted from images in 2008 for one of the regions of interest, Tree1a, for a centred beech tree. In the graphs of values, solid circles indicate data from images captured when the downward shortwave radiation was low, open circles indicate images under high-radiation conditions, and crosses indicate low-visibility images obscured by haze, rain and/or water droplets (low-visibility images were selected manually after visual inspection). The dotted line on DOY 122 indicates the visually selected date for budburst determined using the images on the left, and DOY 318 indicates the selected date for abscission using the images on the right.

The seasonal changes in 12 colour indices from the dominant beech tree derived from the values are shown in Figure 2.3. The meaning of the indices is defined mathematically in Table 2.1. The strength of the red channel was stable over most of the year except during autumn, when a peak was observed for autumn colouring and thereafter decreased with abscission (Figure 2.3A). The strength of the green signal declined gradually over the summer and reached the level of dormancy values after a small negative inflection (Figure 2.3B). The strength of the blue signal showed a negative bimodal distribution with inverted peaks in spring and autumn (Figure 2.3C). The dispersion by low visibility clearly is seen in the strength of green as well as the strength of blue.

The three signals obtained for the HSL colour system showed quite different seasonal patterns. Hue was the least variable from day-to-day of the three (Figure 2.3D). It dramatically increased after day 120, which was consistent with the change observed in the green signal strength shown in Figure 2.3B. Thereafter, while the strength of the green signal gradually decreased over the season, the hue signal continued to increase during the leaf-flushing stage until day 130; thereafter it declined gradually during the remainder of the season (Figure 2.3D). Hue was affected by precipitation, but overall it was less ‘noisy’ than other indices. In winter, the hue was affected by snow cover even on clear days. The saturation signal was more susceptible to visibility than that of the hue (Figure 2.3E), but its seasonal pattern depicted two obvious maxima that indicated the peaks of leaf-flushing and autumn colouration. Saturation values tended to be lower during hazy conditions. Lightness values also displayed large day-to-day variations, with maximal values occurring during the dormant period (Figure 2.3F). Monochrome luminance (Figure 2.3G) showed a similar trend to that of the lightness. The difference between obscure and clear images was hard to distinguish for luminance. Although luminance was expected to show the high density of leaves in the green period, it showed relatively little seasonal variation and was quite noisy.

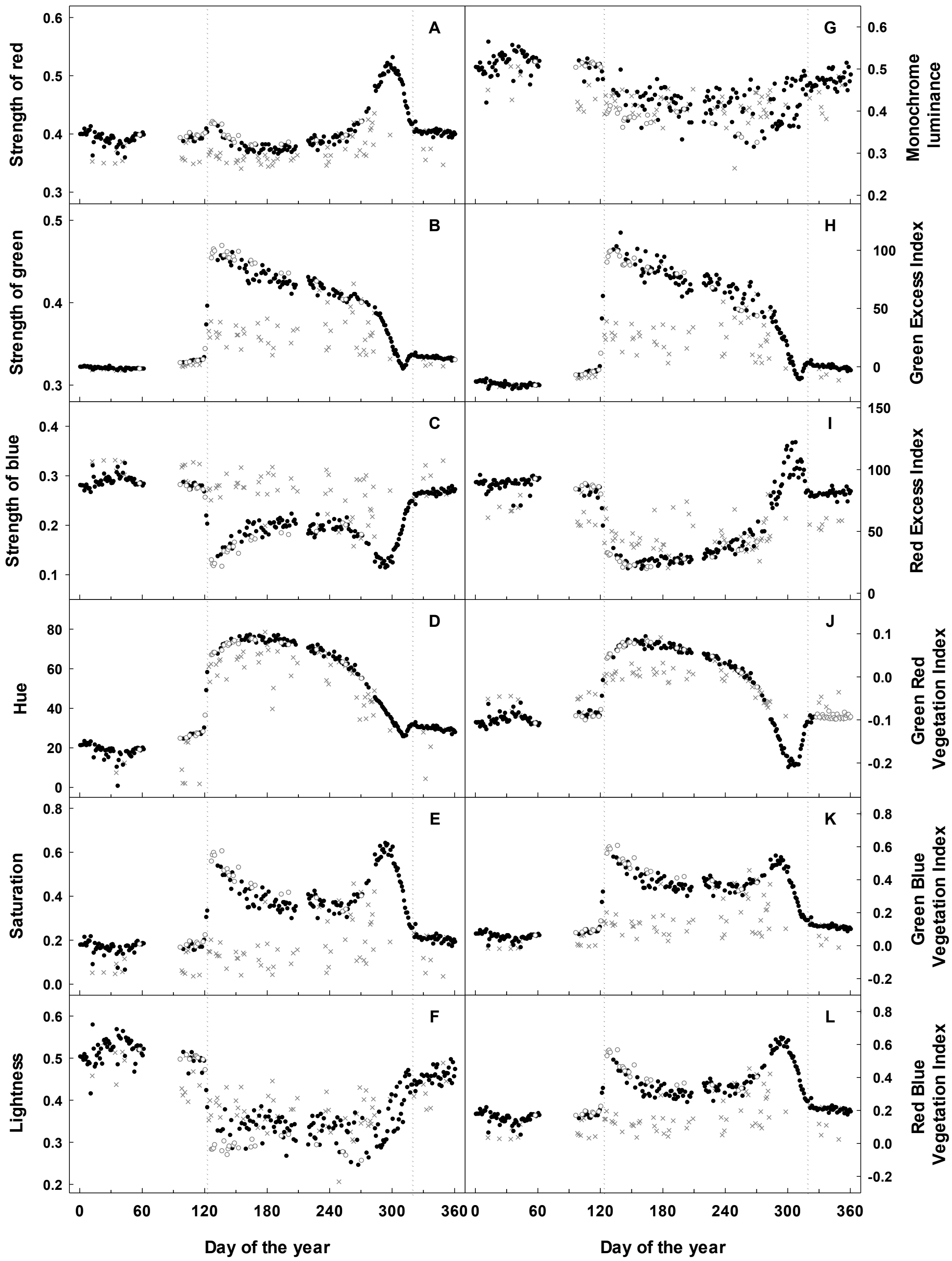

Figure 2.3 Seasonal variations in the colour indices calculated (listed in Table 2.1) in 2008 for Tree1a. Legend as in Figure 2.2.

The Green Excess Index (GEI) effectively detected bud break, showing a dramatic increase at the spring onset; thereafter a continuous decline was observed throughout the season, with a slightly steeper drop in GEI observed during the autumn senescence period (Figure 2.3H). The Red Excess Index (REI) decreased in the leaf-flushing phase and showed a peak in autumn (Figure 2.3I). Over the season the Green Red Vegetation Index (GRVI) flipped from negative to positive at leaf-flushing, and showed a sharp decrease back to negative values during leaf shedding (Figure 2.3J). Interestingly, the most negative values occurred prior to leaf abscission and were more negative than dormancy values. Both the Green Blue Vegetation Index (GBVI) and the Red Blue Vegetation Index (RBVI) had a bimodal distribution in spring and autumn showing trends that were similar to those observed for the saturation signal (Figure 2.3K, L). The dispersion by low visibility is seen in GEI, GBVI and RBVI.

Low-visibility conditions added noise to most indices except strength of red, hue and GRVI, while the difference between the high and low-light conditions was not significant. To quantify fluctuation, we calculated the first derivative for the moving average index excluding low-visibility images (Figure 2.S4 in 2.9). Hue showed the least day-to-day variability, followed by strength of green. Lightness and monochrome luminance showed a day-to-day variability throughout the year, which suggested the difficulty to detect signals of seasonal change.

2.4.2 Spatial variation in seasonal pattern of indices and phenological dates

We combined data of all ROIs into one graph, to illustrate how much the indices varied when the tree examined is in a non-optimal position in the image, being partially shaded or so far away as to be affected by haze (see Figure 2.1). To make the data easier to observe on the graph, the 5-day running averages were plotted rather than the daily data shown in the previous figure (Figure 2.3). The different ROIs showed similar trends to each other (Figure 2.4). Hue showed the least scatter. A study in North American deciduous forests found that the seasonal patterns in strength of red, green and blue at more distant stands were less pronounced (Richardson *et al.* 2009). The same trend appeared in the patterns of all indices; the signals from Tree1 were the strongest followed by Tree2 and Tree3 corresponding to the distance from the camera. Green fraction was significantly influenced by the distance, while hue was less sensitive to the distance.

The estimated phenological dates derived from the seasonal patterns of the indices are presented in Figure 2.5, with the dates of bud break and abscission obtained from visual inspection of the images. Most of the bud break signals derived from images occurred before the visual identification, while most of the abscission signals were later (Figure 2.5A, B). Consequently, the foliage periods visually determined tended to be shorter than those from images (Figure 2.5C). Most indices showed an agreement on the spring peak date, while the peaks of the hue, the REI and the GRVI ccurred later (Figure 2.5D). Autumn peaks were more variable between indices (Figure 2.5E).

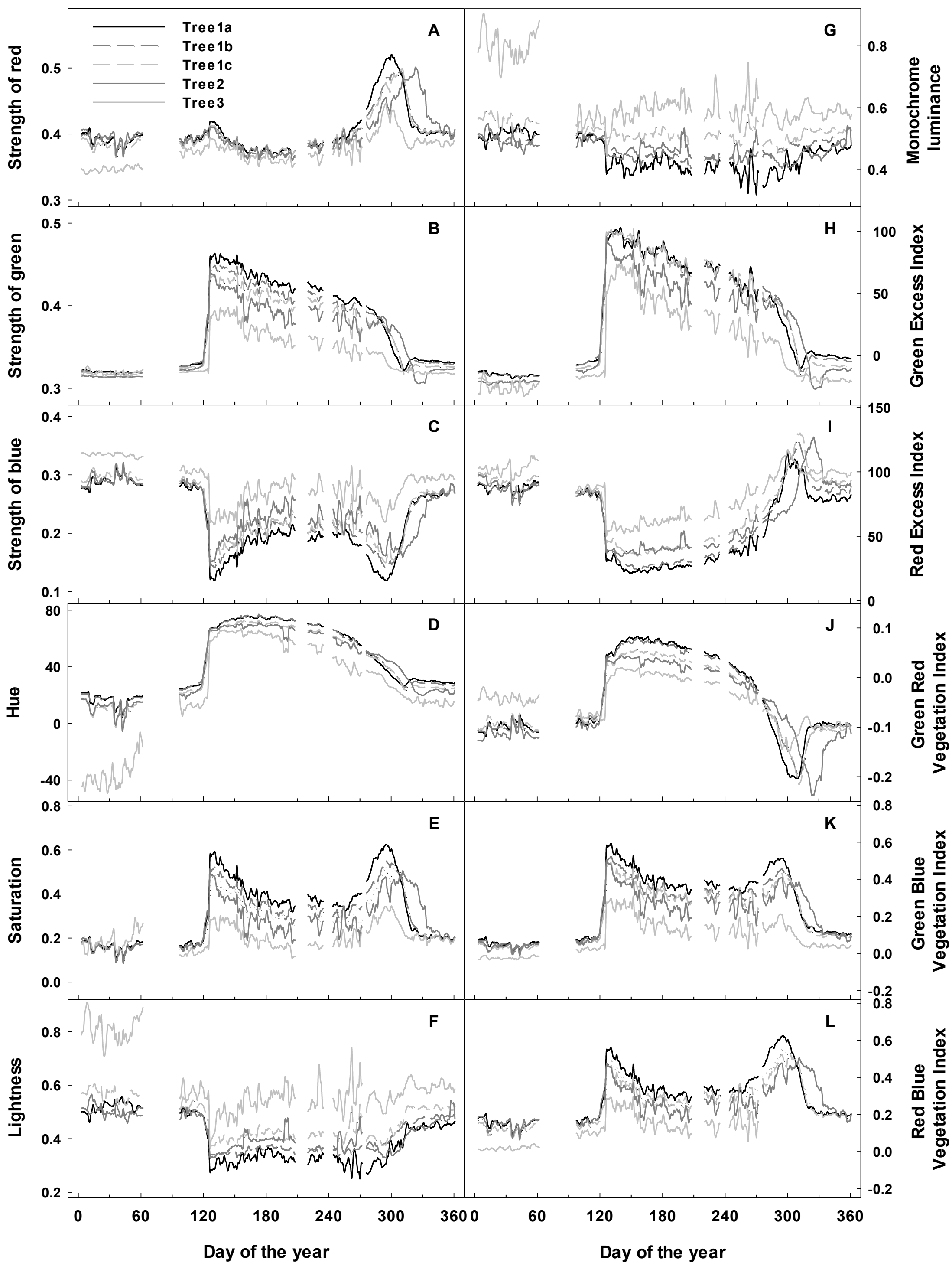

Figure 2.4 Seasonal variations in the colour indices calculated (listed in Table 2.1) in 2008 for all regions of interest extracted from images under high-radiation conditions. Hue values over 180° were converted into negative from 0° (e.g. 350° -> −10°).

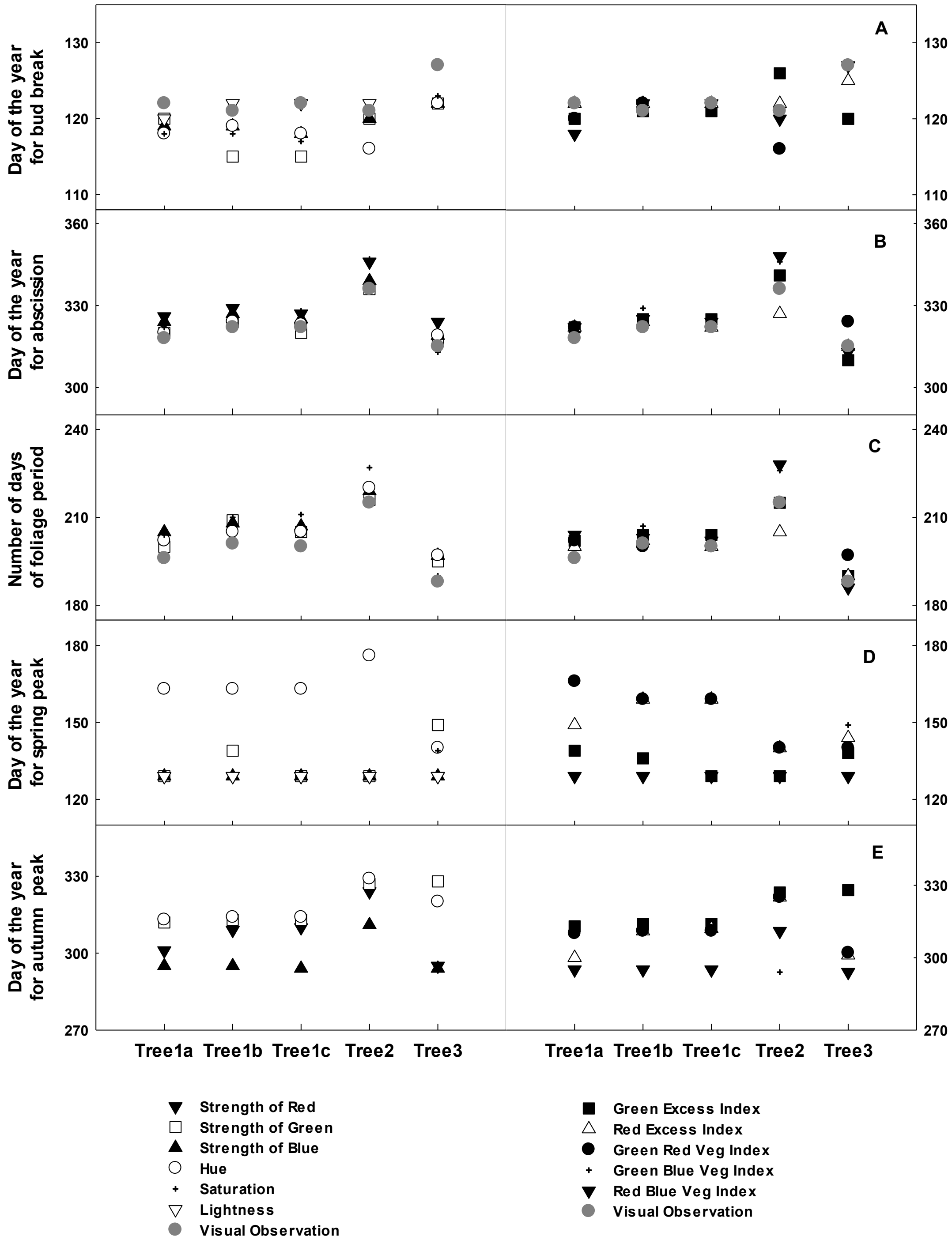

Figure 2.5 Phenological dates estimated by vegetation indices for the five regions of interest. Foliage periods are the numbers of days between bud break and abscission. Dates determined visually from images are also shown for bud break, abscission and foliage period.

2.5 Discussion

There are essentially three approaches to measuring phenological changes in vegetation. The first, and most widely reported, involves direct human observation of dates of bud break, flowering and leaf fall. Analysis of large data sets, usually involving several species at a single location over many years, has enabled generalisations to be made about the relationship between these phenological stages and weather patterns (Menzel 2000; Sparks, Jeffree & Jeffree 2000; Chmielewski & Rotzer 2001). A disadvantage of this approach is that it relies on a somewhat subjective decision of the stages by the observers, and can be influenced by the 'outliers', i.e. those individual plants which happen to be early or late in their phenological behaviour. Moreover, it is labour intensive, although there appears to be no shortage of willing volunteers who are able to carry out daily observations, particularly on garden plants (Hepper 2003).

The second approach uses remotely sensed data from satellites or towers to detect changes in colour (Myneni *et al.* 1997; Zhou *et al.* 2001; Stockli & Vidale 2004). There are disadvantages in this approach too: long time-series of data are hard to acquire because of the limited life span of a satellite-borne sensor; in addition, satellite data are not collected when the landscape is cloud covered. In some respects it is an advantage that the satellite 'sees' a large amount of landscape (spatial resolution is from a few square metres to many square kilometres), as a large sample integrates over many thousands of plants, but species mixtures can affect signal interpretation. Sensors mounted on flux towers, above the canopy, overcome many of the objections that apply to satellite data. Such sensors may be broad-band, like NDVI sensors (Miller, Lane & H.C. 2001), or they may be hyperspectral radiometers (e.g. Motohka *et al.* 2009, Nagai *et al.* 2010a).

The third approach, described in this paper, is relatively new, and involves digital photography. The approach has recently acquired popularity because it can be obtained from public internet-connected cameras (Jacobs *et al.* 2009; Graham *et al.* 2010; Ide & Oguma 2010) and, importantly, it is associated with the rapidly expanding network of flux towers (Baldocchi *et al.* 2005; Richardson *et al.* 2007; Wingate *et al.* 2008; Ahrends *et al.* 2009). Thus phenology can now be linked to photosynthetic and respiratory CO_2 exchange, hence providing a deeper understanding of the controls on the terrestrial carbon cycle. The signals we present are rich in information, indicating not only the classical phenological stages but also subtle changes during the growing season, probably associated with changes in leaf pigments, leaf area and pathogen infection. Moreover, the signals from the camera can be stored indefinitely, providing an archive for subsequent analysis. However, there remains some confusion about which signals are most suitable for analysis, and in the current paper we have attempted to identify the most robust indices. A prime concern is filtering of effects caused by the changing light conditions, especially those associated with bad weather.

We found that ‘hue’ provided a more robust metric than those used by most other research groups who based their indices on simply the strength of the green or red signal. It showed much less scatter during the summer and a very good indication of spring bud break (Figure 2.3). Hue varied between trees by only 25%, whereas all the other indices were either much more variable or they did not change with bud break (Figure 2.4). It is clear that a system such as HSL is theoretically capable of defining any colour as perceived by the human eye. It can cope with variations in brightness and tone, which a simple expression of R, G and B, or a combination of these signals, can never do. In canopy phenology there are situations of light and shade, and the haze caused by scattering of short-wave radiation, which provide much of the information content perceived by humans. It is clear that hue represents the pure colour that leaves and flower present, whilst ‘saturation’ and ‘level’ are influenced by non-biological variables such as radiation flux and direction, and scattering by aerosols. The use of ‘hue’ has, however, been overlooked in the analysis of remotely sensed images, in favour of indices such as NDVI, which was initially developed for satellite sensors with only limited capability of resolving the electromagnetic spectrum. Nowadays, with hyperspectral sensors and colour photography, this traditional approach may not be appropriate.

There was some disagreement between the phenological dates measured by the indices versus purely visual observation of the images (Figure 2.5). The bud break dates assessed by the indices were earlier and the abscission dates assessed by the indices later than those assessed by visual observation, and this can have a significant effect on estimates of canopy duration. The trends coincide with the results of a similar study using green fraction of beech (*Fagus sylvatica* L.) trees in two European forests (Ahrends *et al.* 2008; Ahrends *et al.* 2009). Abscission dates are recognised as being harder to judge than spring signals even by visual inspection, as highlighted by Menzel *et al.* (2006). Presumably this reflects the complexity of the processes whereby leaves are shed, as wind and location-on-tree may be important factors. These inaccuracies in visual assessment may also partly explain the greater departures of abscission dates compared with bud break dates of Figure 2.5.

All indices showed seasonal behaviour. The strength of the green signal was, not surprisingly, a very reliable indicator of bud break and the abscission of leaves. Hue, despite its complex and conditional definition (Table 2.1), was equally good at estimating canopy duration. Immediately after bud break, and immediately before abscission, some of the indices showed very clear maxima. In the case of the green peak after unfolding, this indicates that all of the leaves were fully developed. The gradual decline following the peak (in green indices) may be associated with the maturation of the leaf cuticle and perhaps the progressive ‘weathering’ and ‘contamination’ of leaf surfaces, potentially including the colonisation of leaf surfaces by micro-organisms (Saunders 1971) and possibly the development of negative water potentials in summer (Zakaluk & Sri Ranjan 2008). In crop species, it has been shown that the decline in green is associated with an increase in chlorophyll, as a high optical thickness of chlorophyll makes the leaves appear darker in the green waveband (Kawashima & Nakatani 1998). In the case of the red peak before abscission, we presume that the carotenoid pigments become more apparent as the chlorophyll breaks down (e.g. Archetti *et al.* 2009).

Ecological phenomena relating to the canopy, such as leaf area expansion, leaf shedding, herbivory, disease and tree health can be seen in these images. Monochrome hemispherical images taken from ground-based locations were commonly used for measuring leaf area index (van Gardingen *et al.* 1999). However, monochrome luminance did not show any evidence of the increase of leaf density in this study. Although disease and insect damage were not recorded, it is expected that a decrease in the numbers of leaves will cause a decline in the green strength and GEI, and that any change in leaf colour will have an effect on the hue.

Richardson *et al.* (2009) reported that the change of white balance on the camera setting from 'auto' to 'fixed' reduced the day-to-day variability in the green strength.

Although we used fixed white balance (cloudy), the signals were still noisy even for images captured on only cloudy days, which were less affected by direct sunlight and precipitation. The red and green values were less variable in comparison with the blue values. Consequently, hue and GRVI were not susceptible to weather conditions. It is, however, interesting to note that the distribution of pixel values for each ROI showed some systematic differences depending on the illumination conditions and the season. For example, under high illumination conditions, the distributions of the values of RGB clustered clearly around two separate distributions for summer and autumn/winter, respectively (Figure 2.S3 in 2.9). This resulted in very different means for the two periods but very similar standard deviations around the distributions. Images taken under low illumination conditions appeared more variable seasonally, both in their means and in their standard deviations, with some very narrow and some very wide distributions (Figure 2.S3 in 2.9). Kawashima and Nakatani (1998) reported a good correlation between chlorophyll content and the index derived from red and blue signals for crops in cloudy conditions. However, their reported condition only applied to a fraction of the growing season and they did not extend their findings to the rest of the year. In addition, we think the red- and green-based indices would be better for a long-term, outdoor observation programme, because of the vulnerability of the blue signal to radiation scattered from aerosol optical effects. It is undeniable that the index without the blue signal loses not only the optical effects on blue but also the important colour attribute of leaves. Previous studies (Nakakita 1990; Graham *et al.* 2009) claimed the advantage of using hue. In this study, hue showed robustness in optical conditions in the vegetative period, which is useful for observing leaf condition.

There are some important lessons to be learned from the present work before an automated camera system could be reliably used. First, the use of a standard reference card in the field of view would be a useful aid for quality control. The card would have a black and white target area and also a representation of hues (a colour chart). It might also incorporate a light sensor, to keep track of changes in illuminance of the card. Second, it is clear that camera manufacturers are continuously improving the technology of their product to achieve high-quality photographs, and that different brands and models of camera may not therefore produce the same result. Researchers therefore need to cooperate to share experiences and where possible to make comparisons of camera and lens types. Third, it is notable that the result from any one camera depends to a large extent on the camera settings, and that most ‘convenience’ settings apply a number of corrections. It may be preferable to disable such corrections, including white balance, so that consistent data are obtained.

Further work is needed to relate the colour fluctuations to the pigment system and the physiological activity of the leaves. It may be some time before colour information may be used with weather data to reliably estimate canopy photosynthesis. However, concentrating available cameras at sites where CO_2 flux is being measured by eddy covariance will enable predictive equations to be developed (Nagai *et al.* 2010b).

We conclude that the data from this inexpensive digital camera may be used to detect phenological events with adequate precision, and that other more gradual events which elude the human observer are also detected by the camera. Further work will be required to relate these changes to the pigment concentrations in the canopy, and ultimately to the physiological activity. We propose that of all the candidate colour indices, hue is the most promising for the detection of bud break as it was less affected by atmospheric conditions (e.g. for distant trees seen through bluish haze).

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John Grace is Emeritus Professor of Environmental Biology, in the School of GeoSciences at the University of Edinburgh. His research interests include plant ecophysiology, atmosphere–biosphere interactions and the long-term effects of global change on ecosystem functioning, including carbon sequestration by terrestrial ecosystems.

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2.9 Supplementary materials

Additional supplementary materials were prepared for online access.

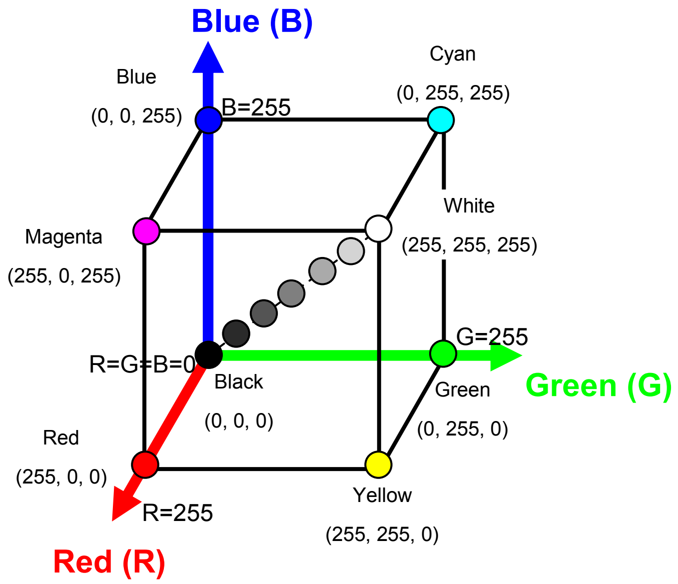
Figure 2.S1 The schematic diagrams of colour spaces used in the present study.

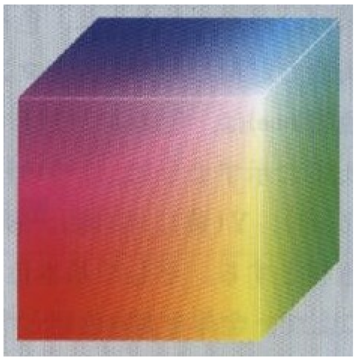
Figure 2.S2 Example images in bud break and abscission seasons

Figure 2.S3 Histogram of red, green and blue values extracted from images using a ROI for Tree1a.

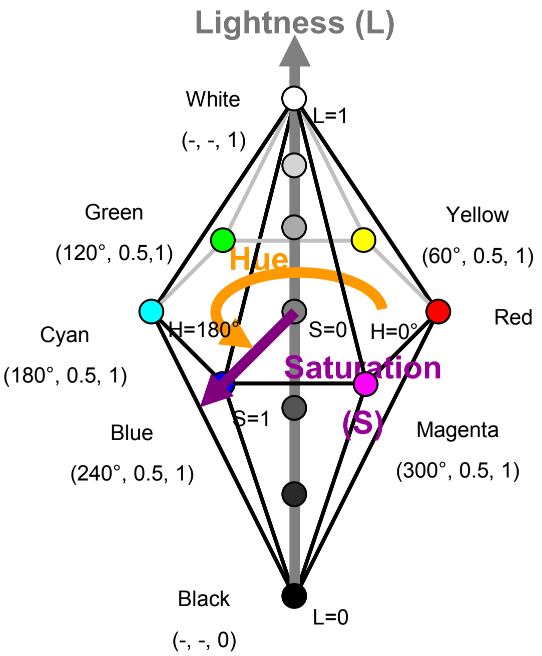
Figure 2.S4 Seasonal variations of first derivatives of colour indices in 2008 for Tree1a.

Red, Green, Blue (RGB) colour system





Hue, Saturation, Lightness (HSL) colour system



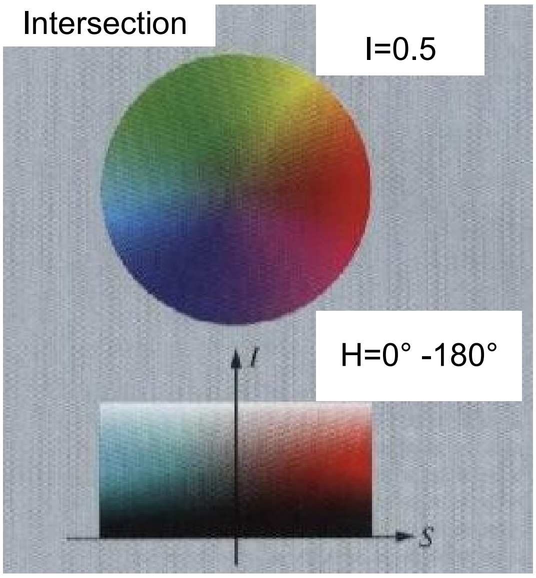


Figure 2.S1 The schematic diagrams of colour spaces used in the present study. For RGB, system of coodinates is x, y, z, where x is red value, y is green value and z is blue value. For HSL, system of coodinates is x, y, z, where x is hue, y is saturation and z is lightness (after CG-ARTS 2004).

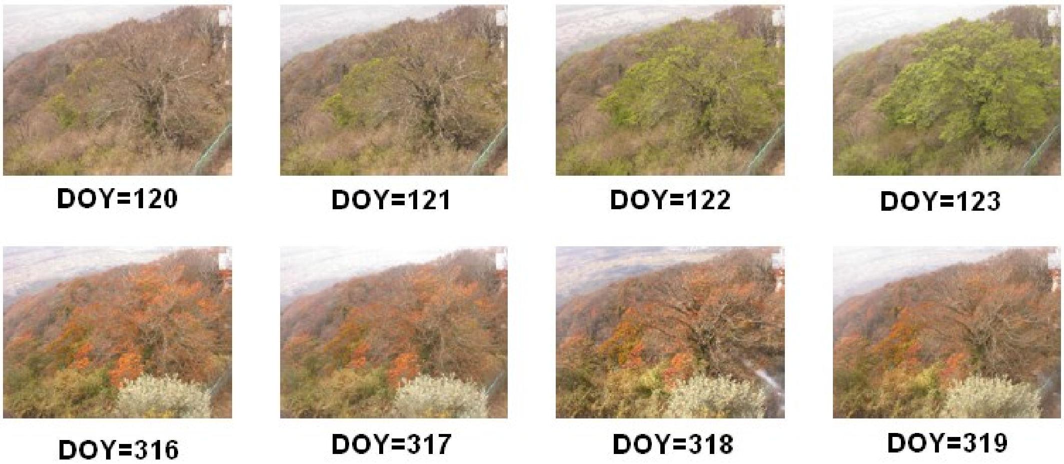


Figure 2.S2 Example images in bud break and abscission seasons

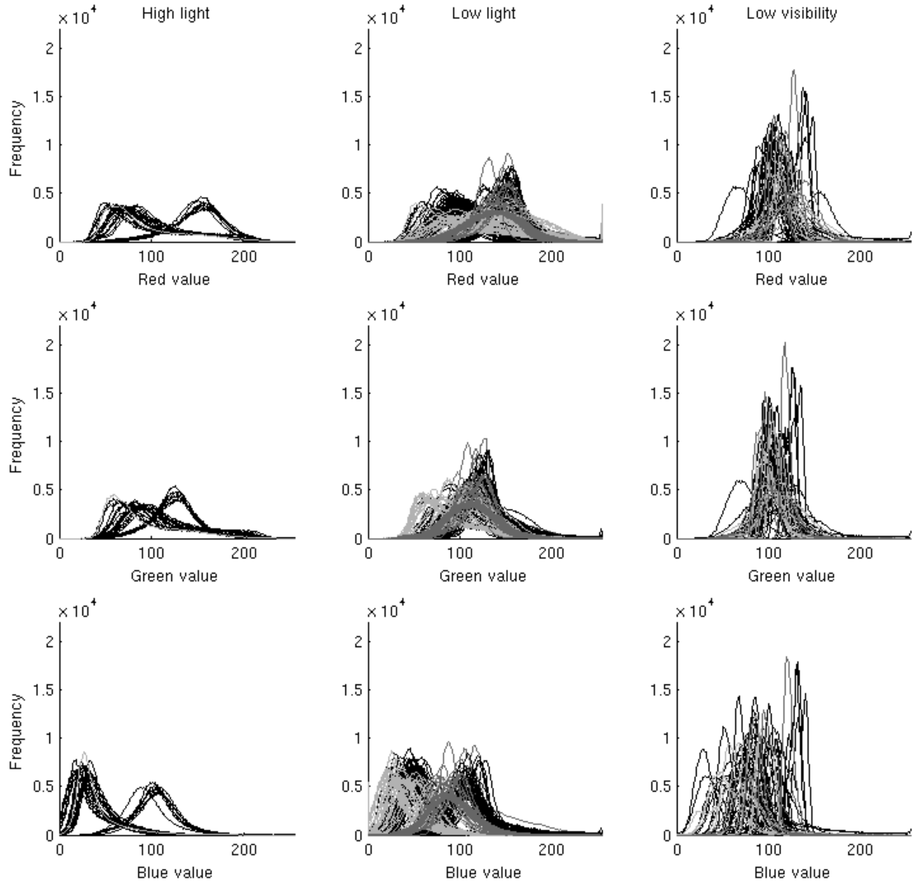


Figure 2.S3 Histogram of red, green and blue values extracted from images using a ROI for Tree1a under low radiation, high radiation conditions and low visibility images obscured by haze, rain and/or water droplets which were selected manually by eye. Black lines are for images taken between DOY 122 and 264, grey lines are for images taken between DOY 265 and 318, and light grey lines are others.

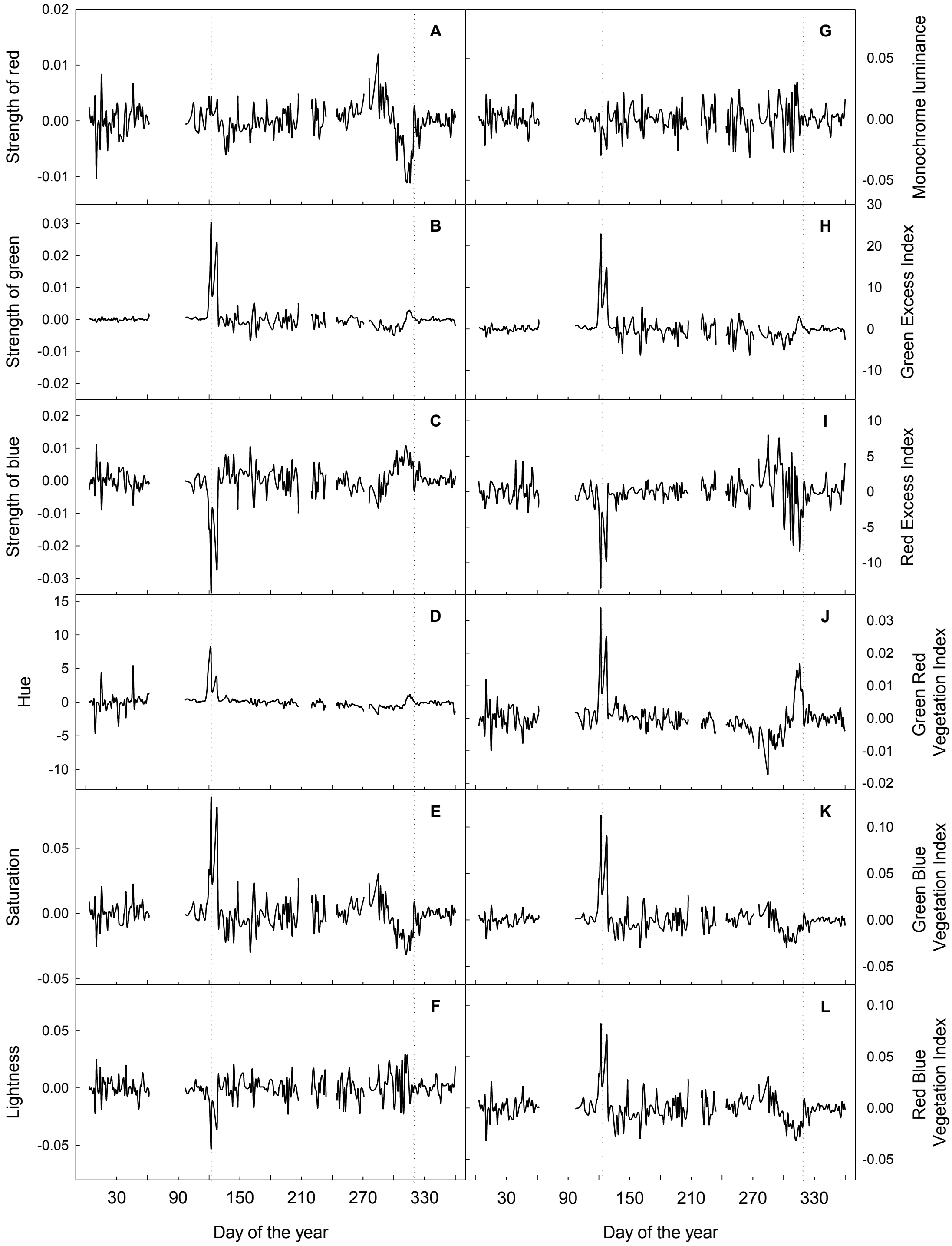


Figure 2.S4 Seasonal variations of first derivatives of colour indices in 2008 for Tree1a.

Chapter 3

Paper II: The relationship between carbon dioxide uptake and canopy colour from two camera systems in a deciduous forest in southern England

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Note: MW, ELE and JILM provided the eddy covariance data and the method. All co-authors revised the draft manuscript. All other work was done by TM.

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3 Paper II: Carbon uptake and canopy colour

3.1 Summary

1. Carbon dioxide flux measurements using the eddy covariance (EC) methodology have helped researchers to develop models of ecosystem carbon balance. However, making reliable predictions of carbon fluxes is not straightforward due to phenological changes and possible abiotic/biotic stresses that profoundly influence tree functioning.

2. To assess the influence of canopy phenological state on CO_2 flux, we installed two different digital camera systems at different viewing angles (an outdoor webcam with a near-horizontal view and a commercial 'fisheye' digital camera with a downward view) on a flux measurement tower in southern England and tracked the visual change of the canopy in this oak-dominated (*Quercus robur* L.) forest over two growing seasons.

3. Changes in the setting of the camera's white balance substantially affected the quality of the webcam images. However, the timing of the onset of greening and senescence was, nevertheless, detectable for the individual trees as well as the overall canopy for both years. The greening-up date assessed from the downward images from a hemispherical lens was ∼5 days earlier than from the horizontal-view images, because of ground vegetation development (not visible in the horizontal view).

4. The effects of a late air frost in 2010 were evident in the canopy greenness, and these led to reductions in daily gross primary productivity (GPP). The cameras recorded differences between individual tree crowns, showing their different responses to the late frost.

5. A major new finding from this work is the strong relationship between GPP and Hue, which was stronger than the relationship between GPP and NDVI.

Key-words: Carbon flux, Digital image, HSL, Hue, Leaf phenology, *Quercus robur*, red, green and blue, Vegetation index

3.2 Introduction

Atmospheric CO_2 concentration is strongly influenced by the seasonality of vegetation (Keeling, Chin & Whorf 1996). It is increasingly important to understand how forests will react to climate change. CO_2 flux measurements using a global network of eddy covariance (EC) systems have provided us with knowledge of the carbon balance of forests. Although the seasonal patterns of carbon flux can be explained in general terms by vegetation physiology, soil and environmental factors, it is harder to understand the interannual variability due to annual variations in the duration of leafing and in the amount of leaves, caused by weather conditions and occasional but often severe biotic stresses that influence the physiological status of trees. Baldocchi *et al.* (2005) proposed that cameras should be installed to record the state of canopies. The relatively low cost of consumer-level digital cameras has made them an attractive proposition for 'near-surface remote sensing' due to the high temporal and spatial resolutions (Richardson *et al.* 2007; Wingate *et al.* 2008; Morisette *et al.* 2009; Richardson *et al.* 2009). The camera network has expanded in North America (Sonnentag *et al.* 2012), Asia (Nagai *et al.* 2011b) and Europe (Wingate *et al.* 2011), and there is now a need to explore the relationships between the recorded images and the productivity and carbon fluxes of the forest.

The timing of biological events and the length of the growing season influence the productivity of all forest ecosystems, in particular deciduous forests (Baldocchi 2008). The study of the timing of biological events such as leaf appearance, flowering and leaf shedding (abscission) is termed phenology. Phenological observations are one of the simplest ways in which the response of species to global warming can be monitored (Menzel 2002). Phenological events are in themselves easy to record, but phenological work has traditionally required field visits with frequent and regular observations of the same organisms at the same location (Sparks, Jeffree & Jeffree 2000). The recent approach of using sensors from satellites provides quantitative data (Myneni *et al.* 1997; Zhou *et al.* 2001; Stockli & Vidale

2004). However, the time resolution is not high, and observations are often contaminated by clouds. Ground-based cameras allow us to record both qualitative (traditional) and quantitative measures of phenology: images may be assessed visually (Ahrends *et al.* 2008) or the time course of vegetation indices can be analysed quantitatively from digital values of red, green and blue (RGB) taken from image files (Richardson *et al.* 2007). The low cost of image capture has encouraged widespread use of cameras in ecological investigations (Ide & Oguma 2010). This also opens up new possibilities: huge sets of data from numerous public outdoor webcams may in the future be accessed to survey phenology at a large geographical scale (Jacobs *et al.* 2009; Graham *et al.* 2010). Vegetation indices based on the spectral reflectance such as the normalised difference vegetation index (NDVI) allow us to quantify phenology using remotely sensed data. However, analogous indices obtained using well-established colour analysis of data are clearly also possible. While these colours indices (Table 3.1) should not be confused with those based on the wavebands of electromagnetic radiation (e.g. NDVI), they may, nevertheless, provide a useful additional source of information.

Early studies used manual or video cameras to record seasonal changes in leaf canopies (e.g. Nakakita 1990; Kawashima & Nakatani 1998). In recent years, however, time-lapse camera systems have enabled quantitative analysis of sequential images for phenological monitoring. Two distinct technologies have been used to provide ‘near-surface remote sensing’ of canopy phenology: (i) real-time webcams connected to a computer network (e.g. Richardson *et al.* 2007, 2009; Jacobs *et al.* 2009, Graham *et al.* 2010), and (ii) commercial digital cameras (e.g. Ahrends *et al.* 2008, 2009; Maeda *et al.* 2008). Here, we aim to investigate the suitability and use of different camera systems. In the case of images from cameras, two vegetation indices are often used: the strength of green relative to the total of RGB is used to detect foliage phenology (e.g. Ahrends *et al.* 2008), while the Green Excess Index (Woebbecke *et al.* 1995) has also been useful (GEI or 2G_RBi, for example, Richardson *et al.* 2009; Migliavacca *et al.* 2011). Conceptually, this ‘strength’ is a representation of colour on three axes, representing RGB referred to as a ‘chromatic coordinates'(Gillespie, Kahle & Walker 1987). The start of the growing season derived from these indices coincided well with the start of the carbon uptake period measured by EC, defined as when gross primary productivity (GPP) is > 0 (Ahrends *et al.* 2008). However, GPP is influenced not only by the state of the canopy but also by the temperature, humidity and photosynthetic capacity, and a model considering these factors is needed to decide which vegetation index is a better proxy of GPP (Migliavacca *et al.* 2011). Graham *et al.* (2009), **Paper I** and, very recently, Saitoh *et al.* (2012) have suggested using an alternative colour system based on the Hue, Saturation and Light aspects of the image (HSL), which is a three-dimensional coordinate system devised by Smith (1978). Hue is an angular scale, 0–360°, expressing colours as perceived by the average human eye, and thus, it is not directly related to spectral distribution. In a previous study, we found Hue detected leaf flushing, performing rather better than other vegetation indices (**Paper I**). This representation of colours was advanced also by Liu & Moore (1990) because of its ability to deal with colour in images containing both sunlit and shaded regions. As colour of leaves depends on their elemental content (e.g. Ollinger *et al.* 2008; Asner, Martin & Bin Suhaili 2012; Hufkens *et al.* 2012b), vegetation indices derived from digital images have the potential to allow detection of nutrient deficiencies and effects of biotic and abiotic stresses on canopy processes.

Although cameras are not calibrated instruments, the results of recent studies using eleven different cameras in a deciduous forest in North America showed that the choice of cameras and image formats made small differences in the detection of phenological change (Sonnentag *et al.* 2012). However, viewing angles of cameras are often horizontal, unlike the viewing angles of satellite sensors (Hufkens *et al.* 2012a). In this case, the lack of information on understorey and ground vegetation phenology may cause problems in matching phenological timings with the satellite-based observations. Hemispherical ('fisheye') lenses were pioneered 50 years ago (Anderson 1964) to measure canopy structure and the penetration of photosynthetically active radiation rather than phenology (see Maeda *et al.* 2008; Nagai *et al.* 2011a, 2012). Hemispherical lenses mounted on downward-viewing cameras give the user choice in selection of regions of interest within the circular image.

The first aim of this study is to compare the phenological data recorded by two different camera systems mounted above an oak woodland: (i) a networked digital webcam with a standard lens and a horizontal view and (ii) a commercial digital camera with a hemispherical lens facing downward. The second aim is to investigate any relationship between the colour of the canopy and the recorded fluxes of carbon dioxide.

3.3 Materials and Methods

3.3.1 Study site

The Straits Inclosure (51°7′ N, 0°51′ W) is located within the Alice Holt Research Forest at an altitude of 80 m and is approximately 60 km south-west of London. The measurement site is affiliated to the FLUXNET/CarboEurope IP network and is included in several other monitoring and research projects. It has a long-term forest health observation plot within the European Network programme (ICP Forests), and it is a UK Environmental Change Network (ECN) site (www.ecn.ac.uk). The surrounding landscape consists of mixed lowland woodland with arable and pasture agricultural land. The site is managed by Forest Research, an agency of the UK Government's Forestry Commission.

Early maps show that the western part of the Straits Inclosure was partly wooded and the east was under agricultural management in 1787, but the whole area was completely planted with oak in the 1820s. It was subsequently re-planted during the 1930s and is now a relatively homogeneous 90-ha woodland block, managed as a commercial lowland oak forest. The main tree species is *Quercus robur* L., and other species, mostly ash (*Fraxinus excelsior* L.) but including *Q. petraea* (Mattuschka) Liebl. and *Q. cerris* L., make up c. 10% of the tree cover. The understorey is dominated by hazel (*Corylus avellana* L.) and hawthorn (*Crataegus monogyna* Jacq.) (Pitman & Broadmeadow 2001). The soil is a surface-water gley (Pyatt 1982) with a depth of 80 cm to the C horizon of the Cretaceous clay (soil series Denchworth and Wykeham). The pH is 4.6 and 4.8 in the organic and mineral horizons, respectively. Mean top height and diameter at breast height (DBH) were 20.5 m and 29.0 cm, respectively, in 1999 at a density of 495 trees per hectare resulting in an estimated basal area of 23.4 m^2 ha^{-1}.

The climate of the region is oceanic, relatively mild and wet. The UK Meteorological Office-affiliated weather station located at the Research Station, approximately 1.8 km from the monitoring site, provides long-term data. In the 30-year period of 1961 through 1990, the mean annual precipitation was 779 mm and the mean annual air temperature was 9.5°C.

3.3.2 Microclimate measurements and canopy state

Environmental measurements recorded at the flux site include the following: wind speed and direction (model WAA151; Vaisala, Helsinki, Finland), wet and dry bulb air temperature (model DTS-5; ELE International, Loveland, CO, USA), above- and below-canopy solar irradiance (tube solarimeter; Delta-T Devices, Cambridge, UK), global solar radiation (model CM2; Kipp & Zonen B.V., Delft, the Netherlands) and net radiation (model DRN-301; ELE International). The fraction of absorbed photosynthetically active radiation (FPAR) was estimated from the midday average solar irradiance above (I_{above}) and below the canopy (I_{below}). To take account of the different absorption of solar and PAR wavebands by the canopy, the formula given by Monteith (1993) was used:

$$\mathrm{FPAR} = 1 - \left(\frac{I_{below}}{I_{above}}\right)^{1.35} \qquad \text{eqn 1}$$

where the exponent 1.35 accounts for the mean effect of the different absorptivities in the PAR waveband and for total solar radiation. The attenuation of radiation in the canopy follows an exponential function (Jones 1992).

$$I_{below} = I_{above} e^{-k\mathrm{PAI}} \qquad \text{eqn 2}$$

where PAI is Plant Area Index, and k is an attenuation coefficient of total solar radiation, so PAI can be evaluated as:

$$\mathrm{PAI} = -\frac{1}{k}\left(\ln \frac{I_{below}}{I_{above}}\right) \qquad \text{eqn 3}$$

Stem area was estimated using the mean of the midday average of attenuation of solar irradiance between January and March (I_{above0} and I_{below0}, respectively), and Leaf Area Index (LAI) was obtained by subtracting stem area from PAI.

$$\mathrm{LAI} = -\frac{1}{k}\left(\ln \frac{I_{below}}{I_{above}} - \ln \frac{I_{below0}}{I_{above0}}\right) \qquad \text{eqn 4}$$

The attenuation coefficient k for total solar radiation was obtained from the attenuation of PAR using previous *in situ* measurements (Broadmeadow *et al.* 2000, k_{PAR}=0.4) using the expression:

$$k = \frac{k_{\mathrm{PAR}}}{1.35} \qquad \text{eqn 5}$$

LAI was also assessed using litterfall traps located within a 20 m radius of the flux tower. Canopy litterfall (leaves, twigs, frass, acorns and residual fraction) was collected in three cone-shaped traps held above the ground vegetation at a height of 1.5 m, each with a collecting surface area of 0.33 m^2. Small cloth bags attached to the traps were collected every 2 weeks during the summer and autumn and subsequently sorted into their constituents. Leaf surface area was measured using a leaf area meter (model MK2, Delta-T Devices, Cambridge, UK), and peak leaf areas were back-calculated from cumulative litterfall (ICP Forests, 2004).

3.3.3 Eddy covariance measurements and data processing

The turbulent vertical fluxes of energy (sensible and latent heat), momentum, carbon dioxide and water vapour were measured continuously at a height of 28 m using the EC technique (Moncrieff *et al.* 1997). The exact details of the system installed at the

Straits Inclosure have been published recently (Wilkinson *et al.* 2012). GPP was calculated as the differences between ecosystem respiration and net ecosystem exchange (NEE, negative indicates net uptake). The GPP term is hereafter called ‘actual GPP’ to distinguish it from modelled GPP. As small fluctuations in positive GPP were observed in winter, the carbon uptake period was determined using an arbitrary GPP threshold of 0.2 gC m^{-2} day^{-1} for a 5-day average; the start of the uptake period was defined as the days on which the average exceeded the threshold for three consecutive days. Photosynthetically active radiation (PAR) was estimated as 0.47 times the measured incident global solar radiation (Biggs *et al.* 1970), and incident radiation use efficiency (RUE) was calculated as:

$$\mathrm{RUE} = \mathrm{GPP}/\mathrm{PAR} \qquad \text{eqn 6}$$

3.3.4 Digital camera systems and settings

Two different digital camera systems (a commercial webcam ‘NetCam’ and a custom-made digital fisheye camera set-up, Automatic-capturing Digital Fisheye Camera (ADFC), Table 3.S1) were mounted in separate weatherproof enclosures at the top of the EC tower at a height of 26 m. The NetCam SC 5MP (StarDot Technologies, Buena Park, CA, USA) was mounted so that it was facing slightly downward in a south-westerly direction, providing a field of view 47° in the horizontal plane. This camera was equipped with a 4–8 mm, 90°–47° wide varifocal auto-iris lens. Exposure was set to *auto*, and image quality was set to 1296 × 960 pixels. Colour balance was initially set to *auto* but changed to *fixed* with settings of red 256, green 180 and blue 256 on 12 March 2010. The camera was networked to a PC, and image capture was controlled using the manufacturer’s DRV software. Images were taken half-hourly between 06:00 and 18:30 GMT, although the subsequent analysis was restricted to the 12:00–13:30 GMT images to minimise effects of low solar angles. The ADFC is a standard fixed-view camera, incorporated in a system designed by the Phenological Eyes Network (PEN, http://www.pheno-eye.org/index_e.html, Tsuchida *et al*. 2005; Nishida 2007), which consists of a compact digital camera (COOLPIX 4500; Nikon Corporation, Tokyo, Japan), a circular fisheye attachment lens (FC-E8, Nikon Corporation, field of view 180°), a waterproof housing and a control system with a PC running the open software PHOTOPC (http://www.lightner.net/lightner/bruce/photopc). It was mounted horizontally facing downward, recording images every hour from 05:00 to 21:00 GMT. As for the NetCam images, only the 12:00–13:30 GMT images were used here. Exposure was set to auto, and digital images were stored as compressed JPEG file (resolution 2272 × 1704 pixels, three channels of 8 bit RGB colour information, and a camera setting of fine image quality). The white balance was set to *auto* in 2009 and changed to *fixed* with the sunny setting on 6 April 2010.

3.3.5 Image analysis

ImageJ (National Institutes of Health, Bethesda, MD, USA; version 1.42q) was used to process the images, and the regions of interest (ROI) were fixed (Figure 3.1). The crowns of two oak trees were ROI in the images taken by both cameras. We extracted RGB digital numbers from the images and calculated the strength of each colour channel (S_{red}, S_{green}, S_{blue}) and Hue (equations are listed in Table 3.1). The strength of a channel is the ratio of the digital numbers of each channel to the total digital numbers of RGB channels, and Hue is one of the dimensions of the HSL colour scheme (see **Paper II**). The change of white balance setting after the first year made a difference to the magnitude of RGB digital numbers. We screened the images using Hue values, which are sensitive to wet conditions where values tend to shift towards the range of blue (180°–270°). By analysing images under hazy and snowy conditions and images with droplets on the lens, a threshold was established for the elimination of the images in which Hue values were larger than 140°. Dates of phenological events were determined by visual inspection of the graph of the annual time course.

Table 3.1 Vegetation indices used and/or discussed in this study

Vegetation index	Formulation		Reference
Strength of red	$S_{red} = n_{red} / (n_{red} + n_{green} + n_{blue})$		Gillespie, Kahle & Walker (1987)
Strength of green	$S_{green} = n_{green} / (n_{red} + n_{green} + n_{blue})$		
Strength of blue	$S_{blue} = n_{blue} / (n_{red} + n_{green} + n_{blue})$		
Hue	$Hue = (b - r) / ((I_{max} - I_{min}) \times 60) + 120$	if $g = I_{max}$	Joblove & Greenberg (1978)
	$Hue = (r - g) / ((I_{max} - I_{min}) \times 60) + 240$	if $b = I_{max}$	
	$Hue = (g - b) / ((I_{max} - I_{min}) \times 60) + 360$	else if $g < b$	
	$Hue = (g - b) / ((I_{max} - I_{min}) \times 60)$	otherwise	
Green Excess Index	$GEI = 2 \times n_{green} / (n_{red} + n_{blue})$		Woebbecke *et al.* (1995)

The terms S_{red}, S_{green}, S_{blue} are chromatic co-ordinates *sensu* Gillespie, Kahle & Walker (1987); n_{red}, n_{green}, n_{blue} are the values of red, green and blue respectively; $r = n_{red} / 255$, $g = n_{green} / 255$, $b = n_{green} / 255$; I_{max} is maximum value of r, g and b and I_{min} is minimum value of r, g and b.

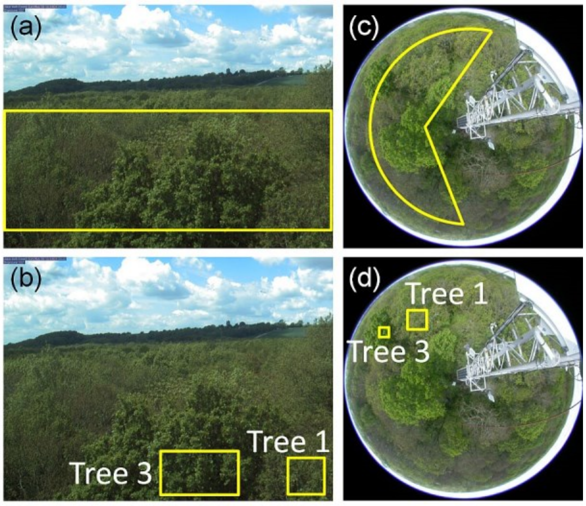

Figure 3.1 Example images and the analysed regions of interest (ROI) for: (a and c) canopy and (b and d) individual trees. (a) and (b) were taken by the NetCam and (c) and (d) were taken by Automatic-capturing Digital Fisheye Camera (ADFC).

3.3.6 Modelling GPP

Daily vegetation indices calculated from canopy-scale images were used to model GPP using the equation for MODIS GPP and NPP products (MOD17A2/A3, Heinsch et al. 2003):

$$GPP_{model} = \varepsilon \times FPAR \times PAR \qquad \text{eqn 7}$$

where ε is the radiation conversion efficiency and FPAR can be derived from measured light interception (eqn 1). Using an approximation detailed in Running *et al.* (2000), and because NDVI generally assumes positive values, FPAR can be replaced by the NDVI:

$$GPP_{model} = \varepsilon \times NDVI \times PAR \qquad \text{eqn 8}$$

The conversion efficiency ε was calculated using simple linear ramp functions of the daily minimum temperature (Tmin) and the daylight average vapour pressure deficit (VPD).

$$\varepsilon = \varepsilon_{max} \times f(Tmin) \times f(VPD) \qquad \text{eqn 9}$$

The ramp functions (f) enable ε to be reduced to take account of the sensitivity of photosynthesis to temperature and humidity. We used the observed Tmin, VPD and maximum RUE for Ɛmax and obtained the parameters of the ramp functions for deciduous broadleaf forest (DBF) from the Biome Properties Look-Up Table (BPLUT) for the MODIS product of vegetation production (Heinsch et al. 2003). To compare with satellite-based data, we obtained the MODIS Land Product Subsets for the Straits Inclosure (Oak Ridge National Laboratory Distributed Active Archive Center (ORNL DAAC) 2010; NDVI (MOD13Q1 and MYD13Q1, 16-day composite, 250-m resolution) and selected those for which product quality was flagged *good*. For deciduous canopies, it is possible to normalise the S_{green} and Hue vegetation indices derived from images, using the maximum and minimum values in each year (VI_{norm})

$$VI_{norm} = (VI - VI_{min}) / (VI_{max} - VI_{min}) \qquad \text{eqn 10}$$

and replacing the NDVI with the analogous VI_{norm}.

$$\mathrm{GPP_{model}} = \varepsilon \times \mathrm{VI_{norm}} \times \mathrm{PAR} \qquad \text{eqn 11}$$

Statistical analysis was performed using SigmaPlot for Windows (Systat Software, Chicago, Illinois, USA; version 11.0).

3.4 Results

3.4.1 Productivity of the forest and the seasonal trend

The GPP in 2010 was 17% lower than in 2009 (Table 3.2), and both were substantially less than the 12-year average annual value (2034 gC m^{-2} $year^{-1}$, Wilkinson et al. 2012). In both years, an outbreak of defoliation by caterpillars of winter moth (*Operophtera brumata* L.) was observed in May and early June, and, noticeably, an infection with oak mildew (*Erysiphe alphitoides* Griffon & Maublanc 1912) followed on some oak trees. The dry weight of insect frass collected in litter traps was approximately 6.5% of that of leaves in both years. Figure 3.2 shows the daily variations in air temperature, precipitation, global radiation, GPP, RUE and LAI estimated from light interception at the site in 2009 and 2010. In 2009, the increase in GPP started on day 103, while the GPP increase in 2010 started 2 weeks later on day 118 with the slower increase in spring temperature. The number of days in excess of 5°C in minimum temperature until the uptake started was similar in the 2 years (23 and 21 days, respectively). A cold spell occurred in the first half of May 2010, and the minimum air temperature dropped to -2°C on day 132, damaging leaves, although the effects were hardly observed in GPP and LAI. The highest daily GPP in 2009 was 18.3 gC m^{-2} day^{-1} on day 165 and that in 2010 was 15.0 gC m^{-2} day^{-1} on day 181 (Figure 3.2c). Autumn 2009 was mild, and the first record of air temperature below zero was 1 day after the carbon uptake finished on day 288. In comparison, there were cold days in mid-October 2010, and the minimum temperature of the day 294 was -3.9°C, although carbon uptake continued until day 307. LAI suggested that the trees kept leaves at the end of the carbon uptake period in 2009, while a sharp decline in LAI was observed before the end of the carbon uptake period in 2010. Although the data from the MODIS product were sparse, the increase in NDVI started earlier than that of LAI, particularly in 2009 (Figure 3.2e).

3.4.2 Canopy observations from two cameras

The colour signals extracted from images taken with the NetCam were influenced by the white balance setting (Figure 3.3a), while those from the ADFC showed distinctive seasonal patterns throughout the 2 years (Figure 3.3b). The images taken by the NetCam with auto balance showed high values in red and small variations in green throughout the year, which made detecting changes in the vegetation difficult. In 2010, the change of white balance from *auto* to *fixed* (dash-dot line) substantially improved the stability of red and blue values in the NetCam images and increased the difference in S_{green} and Hue between winter and summer, making the transition more evident (Figure 3.3a). The images taken by the ADFC were vibrant with either *auto* or *fixed* setting, and the stability of vegetation indices was not affected, although the red values with *auto* setting were lower and the green values were higher than those with *fixed* setting. Some of the scatter was caused by changes in sky conditions (Table 3.S2); in sunlit conditions, the normalised S_{green} was higher but Hue was lower than in cloudy conditions for both cameras. For green canopies, the difference between images in cloudy and sunlit conditions was larger with the ADFC camera than that for the NetCam. After the autumn frost in 2010, S_{green} and Hue from both cameras decreased sharply showing the same trend as the LAI and MODIS NDVI (Figure 3.2e).

The indices for the individual trees overlapping in the NetCam and the ADFC images showed that both camera systems detected the same seasonal trends for the same tree (the results for S_{green} are shown in Figure 3.4). In 2009, S_{green} of tree 1 increased on day 102, peaked on day 127 and after a gradual decline dropped to the baseline on day 300. In 2010, the S_{green} of the same tree increased from day 117 and showed a double peak on day 140 and 178 indicating damage and recovery from the late frost event. Although the magnitudes were different for both camera systems and settings, their trends coincided. Mildew was observed on a tree in the ADFC images from day 200 in 2009. By visual inspection, the damaged crown showed distinctively grey among the other green crowns. The values in S_{green} and Hue also showed a sharp decrease (not shown).

Table 3.2 Summary of the climate conditions, the CO_2 flux measurements and litter collection in the two study years at the Straits Inclosure, Alice Holt Forest, south-east England

	Whole year		Carbon uptake period	
	2009	2010	2009	2010
Climate conditions				
Precipitation (mm y^{-1})	937	747	310	358
Average temperature (ºC)	10.2	9.3	14.1	14.0
Maximum temperature (ºC)	29.0	28.8	29.0	28.8
Minimum temperature (ºC)	-9.8	-9.6	-1.1	-3.9
Global solar radiation (MJ m^{-2} y^{-1})	3949	3856	3033	2761
Carbon flux				
Carbon uptake period (day)			186	190
Carbon uptake start (day of year)			103	118
Carbon uptake end (day of year)			288	307
GPP (gC m^{-2} y^{-1})	1824	1506	1684	1396
NEE (gC m^{-2} y^{-1})	-359	-296	-619	-532
RUE (gC MJ^{-1})	0.98	0.83	1.18	1.08
Litter collection				
Maximum LAI (m^2 m^{-2})	4.4	4.2		
Frass in litter traps (g m^{-2})	29.3	23.5		

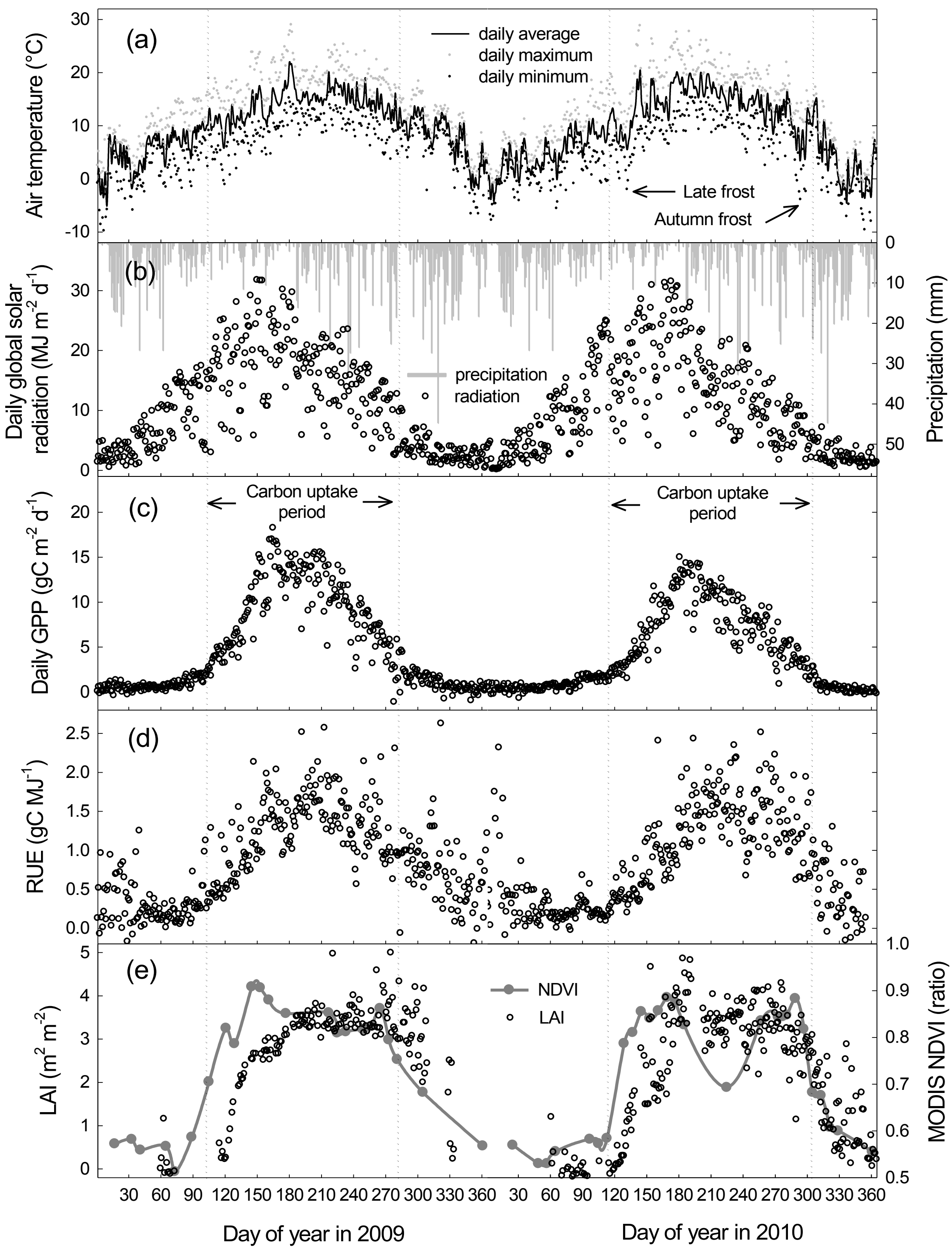

Figure 3.2 Seasonal variations in (a) air temperature, (b) precipitation and global solar radiation, (c) GPP, (d) RUE and (e) LAI estimated from light interception and the MODIS NDVI. Dotted lines indicate the start and end of carbon uptake period determined from GPP.

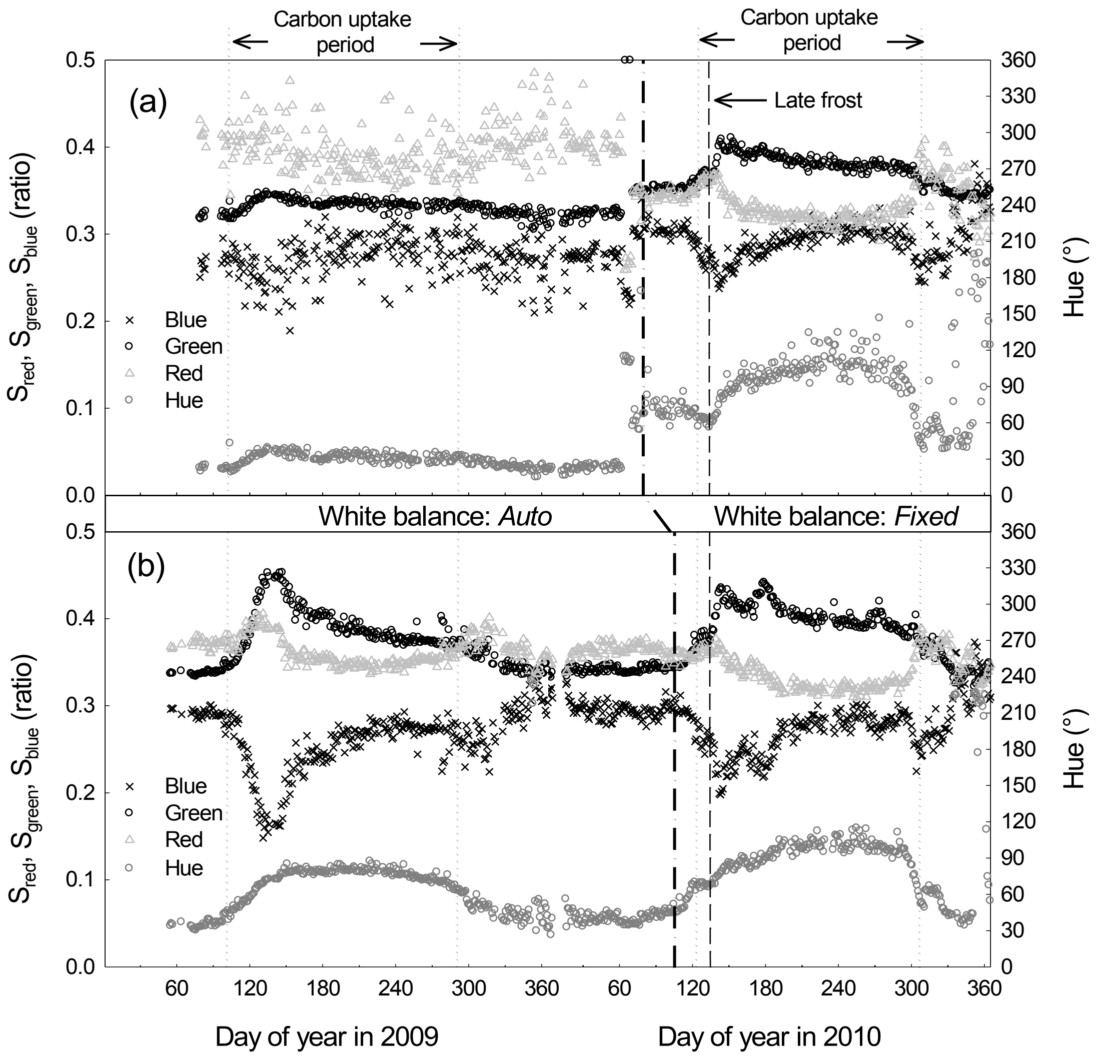

Figure 3.3 Seasonal variations in strength of red, green and blue (RGB) and Hue for the canopy images taken by: (a) NetCam and (b) Automatic-capturing Digital Fisheye Camera (ADFC). Dotted lines indicate the start and end of carbon uptake period determined from GPP. The camera setting of both cameras for white balance changed on the days indicated by dash-dot line. Dashed line indicates the date of late frost event.

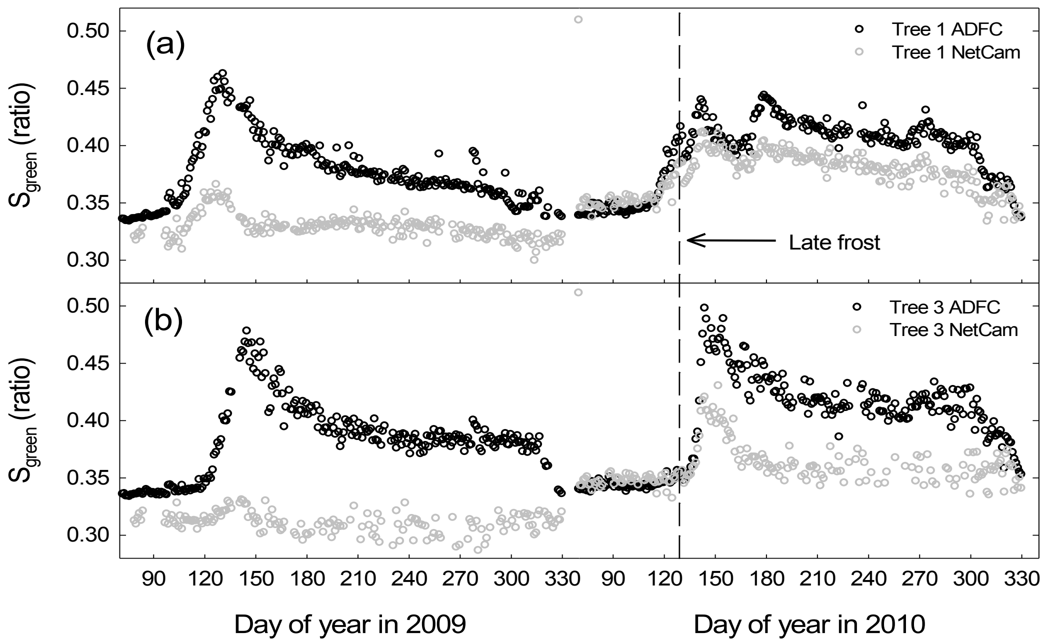

Figure 3.4 Seasonal variations in the S_{green} for two oak trees in both Automatic-capturing Digital Fisheye Camera (ADFC) and NetCam images. Dashed line indicates the date of late frost event.

3.4.3 Seasonal relationships between canopy colour, actual GPP and LAI

In both years and with both camera systems, when the GPP started to increase, the canopy-scale S_{green} and Hue also increased (open circles in Figure 3.S1). The sharp peaks of S_{green} came 30 days earlier than the broader peaks of GPP, while the less rapid increase of Hue in spring with a much broader plateau was a better match to the GPP pattern. However, Hue dropped much later than GPP in the autumn in both years. The match of the pattern of Hue with that of canopy LAI estimated from light interception was good through the summer and autumn (Figure 3.S2), although Hue increased before canopy LAI in the spring.

3.4.4 Using canopy colour to model daily GPP

The modelled GPP estimated from measured FPAR was correlated with the actual GPP (Figure 3.5a), although it overestimated considerably particularly in 2010 (the coefficient of determination R^2 in 2009 and 2010 was 0.68 and 0.60, respectively). The GPP values estimated by the MODIS NDVI correlated less well (Figure 3.5b, R^2 in 2009 and 2010 were 0.36 and 0.48, respectively), and the standard error of the slope was much higher (Table 3.S3). Using the normalised vegetation indices from ADFC images (eqn 10 and eqn 11), the model using S_{green} overestimated GPP over many days in the spring and early summer (Figure 3.5c) showing slopes similar to those computed with MODIS NDVI values (R^2 in 2009 and 2010 were 0.40 and 0.46, respectively). The GPP estimated using the Hue showed a very good correlation with the actual GPP (R^2 in 2009 and 2010 was 0.78 and 0.73, respectively), with no significant difference between 2 years (Figure 3.5d), although there was a consistent overestimation of approximately 15%. Modelling GPP with normalised vegetation index data from the NetCam canopy images in 2010 showed similar results (Table 3.S3), although the slope of the relationship was closer to one.

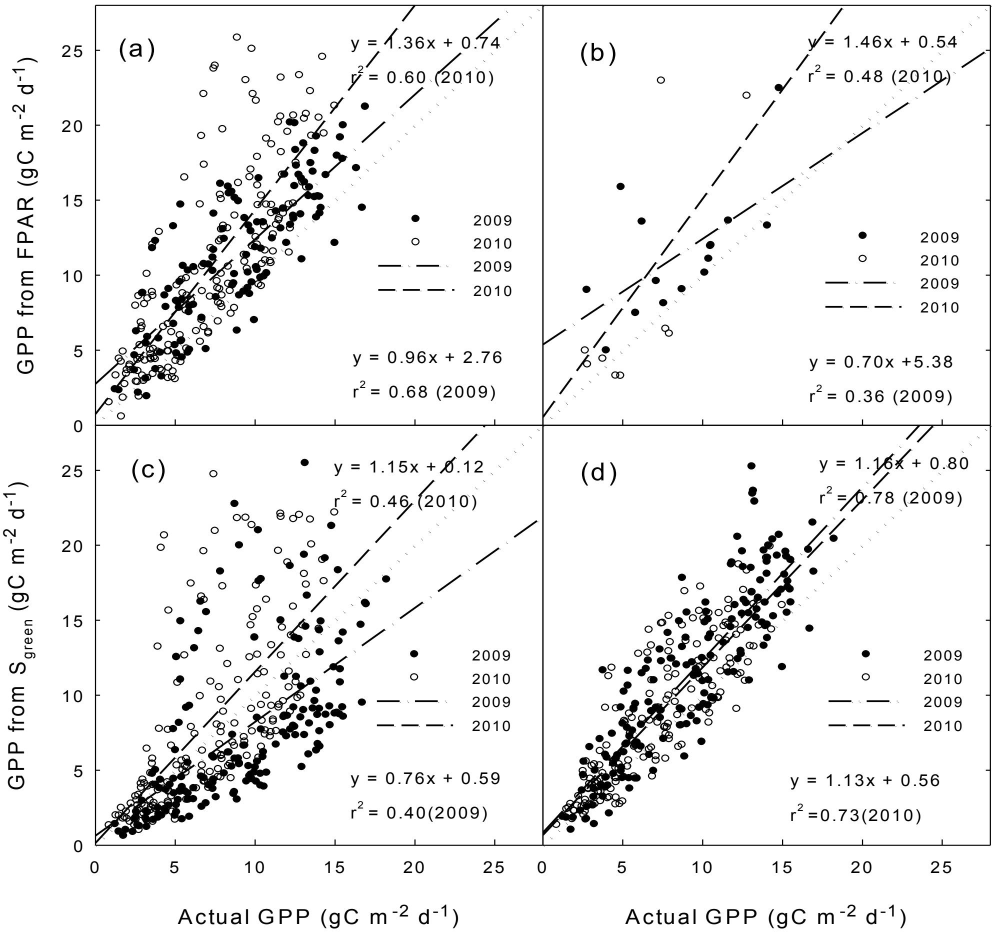

Figure 3.5 Comparison of actual GPP in the carbon uptake period with: (a) GPP estimated from FPAR, (b) GPP estimated from MODIS NDVI product, (c) S_{green} and (d) Hue from Automatic-capturing Digital Fisheye Camera (ADFC) images. Dashed–dotted lines indicate linear regression in 2009, dashed lines indicate linear regression in 2010, and dotted lines indicate y = x.

3.5 Discussion

3.5.1 Observations on leaf canopies using different camera systems

We collected images of a deciduous forest from the top of a flux tower using two different camera systems. They had different fields of view (NetCam, 45°; ADFC, 180°) and were oriented differently. The NetCam was fixed facing south-west, that is, the direction of the prevailing wind and the predominant direction of the flux footprint. However, in the SW orientation, the camera faced the sun and received the forward-scattered signal, which may be less useful than the back-scattered signal that predominately contains reflected rather than transmitted radiation. The choice might therefore be between (i) a rotating NetCam and (ii) a hemispherical lens that offers the choice of viewing angle. The fisheye lens provides images with a distorted geometry, which limits the image areas available for analysis, and most data were collected from vegetation immediately below the camera (Figure 3.1). However, this viewing angle has the advantage of detecting the earlier greening of the ground flora in the spring (Figure 3.3). Although the NetCam covers more distance, and with little distortion, the sideways-looking images taken by the NetCam are still limited in the number of crowns recorded and do not capture the understorey and ground vegetation. However, and reassuringly, when the same tree crowns were examined (Figure 3.4), image analysis from both cameras detected the same phenological timing despite the angle of view differences. The possibility of setting NetCams in a fixed position and with a narrow field of view to focus on individual buds is closer to the traditional requirement of phenologists, which is to capture with fine resolution the state of the forest canopy and to permit the recording of bud break and abscission dates for individual species.

The white balance setting affected the quality of images as described by Richardson *et al.* (2009), which emphasises the importance of protocol standardisation (e.g. PhenoCam http://phenocam.sr.unh.edu). However, the effect of changing the white balance differed between the webcam and the digital camera, and uncertainties still remain when making observations using non-calibrated commercial camera systems. We checked the colour responses of the NetCam using standard colour charts. With the ‘auto’ colour balance setting of the NetCam, colours were represented satisfactorily, but with the colour balance ‘*fixed*’ as described in the methods section, we found that green colours were faithfully reproduced, while yellow was poorly represented. Although calibration panels have been proposed as a solution for different light conditions, Ahrends *et al.* (2009) pointed out the difficulty of using them, as images from their calibration panel saturated in bright light. The distance from objects can influence colour values (Richardson *et al.* 2009, **Paper I**), and a possible degradation of camera sensitivity over time has been suggested (Ide & Oguma 2010). Notwithstanding these difficulties, we found that S_{green} and Hue showed similar seasonal patterns despite differences between cameras and radiation geometries; however, S_{red} and S_{blue} varied. Overall, supporting the previous studies, the results here show the robustness of camera observations for recording canopy phenology.

3.5.2 Camera monitoring of biotic and abiotic stress events

It is evident that continuous camera records of the canopy state can also help us detect the impact of biotic and abiotic stresses (Hufkens *et al.* 2012b). In this study, although the litterfall observations suggested substantial loss of leaf mass from trees due to insect herbivory, it was not possible to detect the defoliation from the image analysis, partly because the canopy was still developing at this time, and defoliation did not cause any separate colour change. However, visual inspection of the leaves in the NetCam images did show leaf damage, although this would be hard to quantify. In photographic standards for assessing the proportion of foliage damage (Innes 1990), the sample photograph for ten percentage foliage loss is hardly distinguishable from healthy crowns; however, once severe crown loss occurs, the damage would be detected by canopy image analysis. In contrast, the grey typical of the oak mildew attack changed the colour of the foliage of affected trees and was detectable in the images. Therefore, the impact of other stresses such as lack of nitrogen, saltwater spray or inundation, that change leaf colour, would also be detectable from such automatic canopy image capture. In addition, the spatial information in images can help identify differences between trees in the impacts or responses, as shown in the response to frost damage (Figure 3.4). Some early flushing trees were damaged and then recovered; some trees avoided the stress due to their late bud break. Observations using camera systems would be useful to track the response of trees in different varieties and provenances to abiotic stresses and also extreme events such as typhoons (Ide & Oguma 2010).

3.5.3 Carbon flux and canopy colour

The timing of the spring rise and autumn decline in CO_2 uptake approximately followed the seasonal pattern in S_{green} and Hue, suggesting that indices based on these attributes may be used to estimate the seasonality of GPP. As the rate of photosynthesis depends not only on the state of the canopy but also on the solar radiation input, it would be surprising to obtain a good agreement between the GPP and any index of colour or of leaf amount alone. In this case, S_{green} reaches a maximum before the peak of GPP, while Hue peaks somewhat later than GPP. This early S_{green} peak coincides with leaf expansion, when the cuticle may not be fully developed and the leaves have not yet been coated by deposition of particles from the atmosphere or colonised by microflora. Later, when leaves are fully expanded and solar radiation input is higher, the maximum photosynthetic performance occurs. We have shown that the peak Hue value shows when the leaves are in the mature 'dark green'. At some study sites, the peak of S_{green} coincided with the GPP peak (e.g. Ide *et al*. 2011; Migliavacca *et al*. 2011), but in others, as here, GPP lagged behind the peak of S_{green} (e.g. Ahrends *et al.* 2009; this study). Analysing images of three deciduous tree species, Nagai *et al.* (2011a) reported that the peak of S_{green} occurred earlier than both the peak of LAI and the peak of leaf chlorophyll content. In the first case, the rapid growth of LAI may have shortened the lag. Some physiological studies revealed that the development of full photosynthetic capacity took more than 50 days after the bud break (Morecroft, Stokes & Morison 2003; Muraoka *et al.* 2010). Compared with the sharp increase in S_{green}, the values of Hue changed from the region of yellowish green to the region of dark green gradually. This suggests a possible relationship with the slow development of leaf pigments.

It is surprising that the image-derived vegetation indices can be better predictors of GPP than FPAR itself. This may be due to the low spatial sampling intensity of below canopy radiation employed here to derive FPAR. However, even extensive sampling of below-canopy radiation using solarimeters or broadband sensors would not detect the change in leaf reflectance caused by physiological changes, pigment changes and colonisation of oak leaves by fungi. In this study, the S_{green} showed a rapid increase at the time of leaf flushing, and the peak often preceded the peak of LAI. On the contrary, the gradual increase of Hue paralleled the trends of LAI. Moreover, Hue does not show the pronounced early peak with a drop off in summer that S_{green} and other indices based on the green channel values do (**Paper I**). Furthermore, using camera image–derived vegetation indices to model daily GPP from incident light and conversion efficiency showed that Hue was a considerably better proxy for fractional light interception than S_{green} (Figure 3.5). This agrees with the good match that Hue gives to the pattern of LAI, although it should be noted that the light interception measurement, from which LAI is derived, was only at one location at the flux site, and not across the whole of the CO_2 flux footprint. Of all the expressions of canopy colour, Hue is the one that seems to have the greatest utility, providing a means to calculate GPP which worked well for both years of study. Further research at other sites is needed to explore whether such a good relationship always exists, as it may be site and time specific. Of particular concern is the necessity to scale the VI values to the maximum and minimum observed for the site. While some researchers may consider this an unacceptable degree of empiricism, we believe it offers a useful approach worth further assessment.

3.6 Conclusions

At this deciduous woodland site, there was only a moderate relationship between NDVI from MODIS and the actual GPP over 2 years. However, vegetation colour indices calculated from digital camera images showed better correlation with GPP. In particular, the Hue parameter was an excellent predictor of GPP over 2 years. We have shown that the digital camera is an important aid in monitoring canopy condition and physiology especially when supplementary data from non-imagery devices are available, including various broad- and narrowband sensors (e.g. Garrity, Vierling & Bickford 2010; Ryu *et al.* 2010). It has the advantage of revealing a quantifiable image of the canopy as well as a set of derived reflectance indices. Thus, it enables researchers to link reflectance change to 'real' phenology and also reveals such occurrences as attack by disease and damage by storms.

3.7 Acknowledgements

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3.9 Supporting Information

Additional supporting information was prepared for online access.

Figure 3.S1 Seasonal variations in GPP with the normalised S_{green} and Hue in the canopy for the images taken by ADFC.

Figure 3.S2 Seasonal variations in LAI with the normalised S_{green} and Hue in the canopy for the images taken by ADFC.

Table 3.S1 Characteristics of the two camera systems used in this study.

Table 3.S2 Normalised S_{green} and normalised Hue for the whole canopy area in different sky conditions.

Table 3.S3 Fitting statistics of the GPP model.

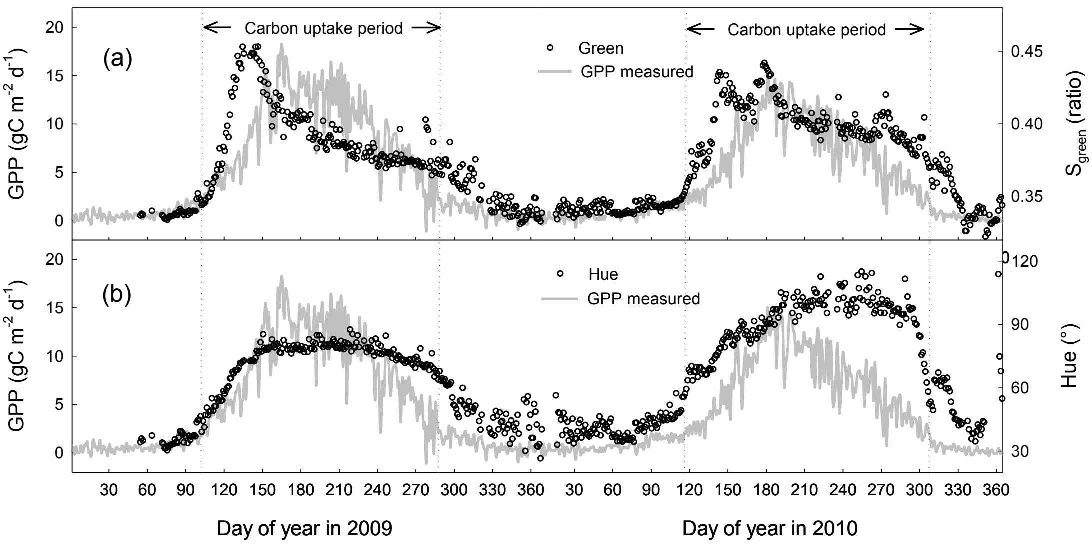

Figure 3.S1 The schematic diagrams of colour spaces used in the present study. For RGB, system of coodinates is x, y, z, where x is red value, y is green value and z is blue value. For HSL, system of coodinates is x, y, z, where x is hue, y is saturation and z is lightness (after CG-ARTS 2004).

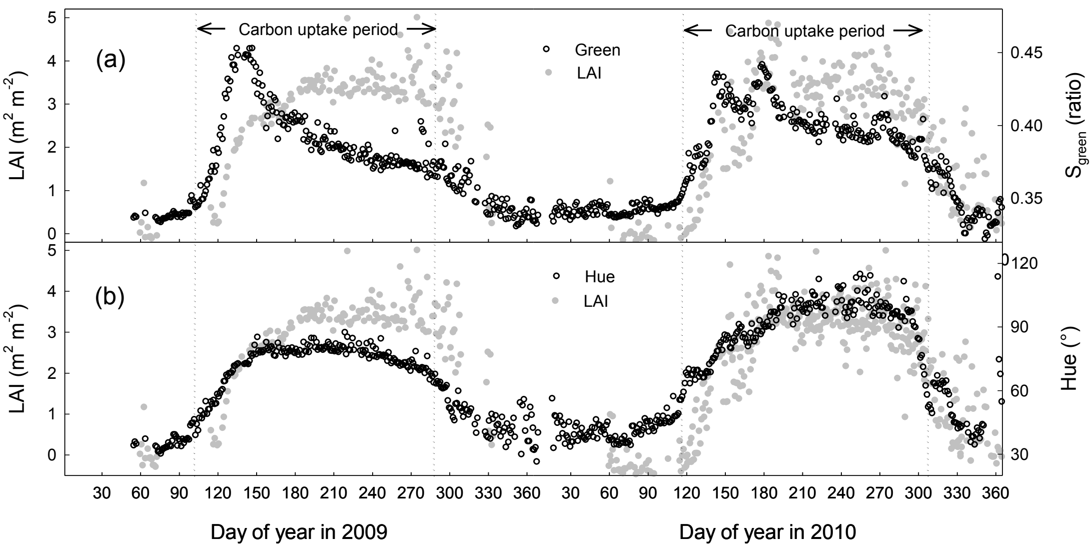

Figure 3.S2 Seasonal variations in LAI with the normalised S_{green} and Hue in the canopy for the images taken by ADFC.

Table 3.S1 Characteristics of the two camera systems used in this study.

	NetCam	Automatic-capturing Digital Fisheye Camera (ADFC)
Maker	StarDot Technologies, USA	Nikon Corp, Japan
Model	NetCam SC 5MP	COOLPIX 4500
Image sensor	CMOS	CCD
Lens focal length	4–8mm	7.85–32 mm
Attached lens	-	Nikon FC-E8 0.21x Fisheye Lens
Water proof case	StarDot Technologies, USA	Hayasaka Rikoh, Japan
Exposure setting	auto	auto
Colour alance/White balance setting	auto→fixed (changed on 12th March 2010)	auto→sunny (changed on 6th April 2010)
Camera angle	near-horizontal	vertical downwards
Image format and size	JPEG format 1296 × 960 pixels	JPEG format 2272×1704 pixels

Table 3.S2 Normalised S_{green} and normalised Hue for the whole canopy area in different sky conditions.

Year		NetCam			ADFC		
DOY		S_{green} Mean (SE)	Hue Mean (SE)	N	S_{green} Mean (SE)	Hue Mean (SE)	N
2009							
a. 132-133	sunny	0.89 (±0.025)	0.71 (±0.013)	4	0.94 (±0.035)	0.45 (±0.014)	3
	cloudy	0.92 (±0.010)	0.74 (±0.010)	4	0.88 (±0.022)	0.49 (±0.004)	5
b. 231-232	sunny	0.36 (±0.020)	0.37 (±0.015)	4	0.39 (±0.005)	0.58 (±0.009)	4
	cloudy	0.71 (±0.017)	0.88 (±0.223)	4	0.37 (±0.003)	0.55 (±0.011)	4
c. 300-301	sunny	0.53 (±0.095)	0.39 (±0.065)	3	0.20 (±0.025)	0.25 (±0.009)	3
	cloudy	0.64 (±0.029)	0.49 (±0.062)	5	0.27 (±0.014)	0.27 (±0.020)	5
2010							
a. 147-148	sunny	0.81 (±0.009)	0.41 (±0.011)	4	0.80 (±0.013)	0.55 (±0.006)	4
	cloudy	0.75 (±0.010)	0.53 (±0.024)	4	0.68 (±0.016)	0.66 (±0.011)	4
b. 241-242	sunny	0.57 (±0.025)	0.57 (±0.023)	4	0.60 (±0.022)	0.76 (±0.013)	3
	cloudy	0.56 (±0.016)	0.74 (±0.020)	4	0.46 (±0.007)	1.00 (±0.020)	5
c. 307-308	sunny	0.21 (±0.014)	0.05 (±0.008)	3	0.30 (±0.008)	0.28 (±0.016)	4
	cloudy	0.22 (±0.009)	0.08 (±0.008)	5	0.33 (±0.009)	0.31 (±0.018)	4

Table 3.S3 Fitting statistics of the GPP model.

Model base	Year	R^2	Slope	RMSE ($gC\ m^{-2}\ d^{-1}$)	N
FPAR from light interception	2009	0.69*	0.97	2.67	127
	2010	0.60*	1.36	3.98	174
MODIS NDVI	2009	0.37	0.71	3.42	15
	2010	0.48	1.46	5.17	15
S_{green} from ADFC	2009	0.40*	0.76	4.14	175
	2010	0.46*	1.15	4.46	178
S_{green} from NetCam	2010	0.39*	0.98	4.45	179
Hue from ADFC	2009	0.78*	1.16	2.71	175
	2010	0.73*	1.13	2.44	178
Hue from NetCam	2010	0.70*	0.99	2.33	179

* Significant ($P < 0.001$).

Chapter 4

Paper III: Sensitivity of colour indices for discriminating leaf colours from digital photographs

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4.1 Abstract

1. Digital images of tree canopies have been analysed to understand how forest phenology responds to climate change. Researchers have used different colour indices to carry out quantitative analyses, but uncertainties over the performance of the various indices are hampering progress in their use.

2. To compare the various indices under controlled conditions, we carried out camera experiments using a set of standard colour charts as model leaves for different stages: emerging leaves, yellowish green; newly expanded leaves, green; fully mature leaves, dark green; senescent leaves, yellow. Two models of cameras, a compact digital camera and a surveillance 'live image' camera were used, and photographs were taken by two cameras for each model under sunny or overcast conditions with two colour balance settings. The indices were also compared with those derived from spectral reflectance.

3. Colour indices based on green such as S_{green} (the ratio of green to total digital number) were strongly influenced by camera models and were less sensitive to the leaf colours. High values of S_{green} were found for emerging and newly expanded leaves. However, S_{green} took similar high values for the mature and senescent replica leaves, highlighting its poor ability to identify the change of colour in autumn. Among the indices, Hue distinguished leaf colour samples with only a small influence of camera models, colour balance setting and sky conditions. Spectral-based Hue was also sensitive to the gradation of leaf colours and showed a good correlation with Hue from images regardless of the camera model and the balance setting. Remarkably, primitive digital number of red, N_{red}, also discriminated leaf colours well, with a small influence of the factors investigated here, showing a good correlation with the reflectance of the red band, except from images taken by the surveillance cameras with auto balance.

4. Although green-based indices have been often used to quantify canopy phenology in previous studies, Hue was a robust index across images, was well correlated with spectral reflectance indices and worked better to discriminate leaf colours. We recommend using Hue as a colour index for its sensitivity to tracking different stages of leaf development.

Key-words: Leaf phenology, Digital image, Spectral reflectance, Munsell Colour Chart, Colour index, RGB, HSL, Hue, Green index

4.2 Introduction

Forests have a significant role as carbon sinks (Pan *et al.* 2011). It is crucial to observe the seasonal change or phenological cycle of forests to study how forests respond to recent climate change. The length of the growing season of trees is an important variable that can influence carbon uptake and release by forests (Piao *et al.* 2008). Satellite observations of terrestrial ecosystems attempt to determine the seasonal changes occurring in vegetation. However, remotely sensed data are often contaminated with clouds and the temporal resolution is not sufficient enough to track the rapid seasonal development of leaf canopies. There is increasing interest in the use of digital cameras to observe seasonal change of terrestrial ecosystems, because they can provide images with high temporal frequency at a relatively low cost (Wingate *et al.* 2008; Morisette *et al.* 2009; Richardson *et al.* 2013). Images can provide not only a visual record but also a numerical dataset of phonological development employing a technique of quantitative analysis pioneered by Richardson *et al.* (2007).

To express the colour from the red, green and blue (RGB) information of digital images, researchers have used a number of different indices, the performance of which remains uncertain (Richardson, Klosterman & Toomey 2013). The strength of the green channel relative to the total of digital numbers or chromatic co-ordinates of green (Gillespie, Kahle & Walker 1987), has been used to detect the period between budbreak and abscission (e.g. Ahrends *et al.* 2009; Richardson *et al.* 2009), while the Green Excess Index or 2G_RB (Woebbecke *et al.* 1995), which emphasises the difference between green and red/blue, has also been used widely (e.g. Richardson *et al.* 2009; Ide & Oguma 2010). The strength of green shows sensitivity to the effects of environmental conditions on forest canopies, e.g., showing a decline caused by frost damage and a subsequent post-frost recovery (Hufkens *et al.* 2012; Mizunuma *et al.* 2013). Although an increase of green-based indices was evident with the onset of leaves, the sharp increase did not agree with the gradual increases of chlorophyll development in a deciduous forest (Nagai *et al.* 2011) and peaks of these indices were observed earlier than the peaks of daily gross primary productivity (GPP) from the carbon flux measurements (Ahrends *et al.* 2009; Mizunuma *et al.* 2013). In autumn, the increase in the strength of red coincided with the decline of chlorophyll content, whereas no significant correlations were seen for green-based indices during the gradual decrease after the onset peak (Nagai *et al.* 2011). Therefore it is not clear that green-based indices are sensitive to the changes occurring during leaf maturarion or senescence. Meanwhile, other studies transformed the RGB into the HSL (Hue, Saturation, Lightness) colour system (Smith 1978) and demonstrated that Hue showed significant potential for estimating leaf area from side-view images (Graham *et al.* 2009) and a seasonal transition in Hue showed a trend similar to that of chlorophyll development of deciduous leaves (Nagai *et al.* 2011). In a recent study, we used the HSL colour scheme to track the changes in canopy development in a deciduous forest and to relate this to the rate of canopy photosynthesis; we discovered that Hue was a more useful expression of leaf colour to estimate carbon uptake than the indices previously used by others (Mizunuma *et al.* 2013). More tests are required to evaluate which colour index is sensitive to discriminate leaf colours.

One of the issues in this area of research is that camera systems are essentially non-calibrated sensors, whose characteristics are known only to the maker, and may be guarded for commercial reasons. This is in contrast to spectro-radiometers which are calibrated against a standard lamp or other sources of irradiance. Consequently, it may be difficult for researchers to compare their work with that of others. In conventional digital cameras the infrared is filtered out and the RGB signals from the sensors are adjusted to suit human perceptions. In fact, camera comparison in a deciduous-dominated forest revealed the values of green index varied significantly between different camera models (Sonnentag *et al.* 2012). On the other hand, comparison between indices derived from images and indices derived from spectral reflectance showed that the differences in Hue are smaller than the differences in the green index (Saitoh *et al.* 2012). Some indices may be more susceptible to change depending on the particular optical equipment but other indices may be less so. In terms of large-scale monitoring, there are attempts to use different types of outdoor cameras installed for various purposes such as surveillance, tourism promotion and wildlife conservation (Jacobs *et al.* 2009; Graham *et al.* 2010; Morris *et al.* 2013). A robust colour index unaffected by cameras and illumination conditions is needed for use of a wide variety of cameras.

In this study we present a comparison of several colour indices, and two models of camera using a set of standard colour charts as model leaves to express the different leaf status. The colour charts are rigorous standards and therefore facilitate reproducibility. In this way, we were able to explore the effects of camera model, camera setting, and conditions of illumination on colour indices. With a comparison to colour indices derived from spectral measurements, we were also able to comment on the relative power of the colour indices in discriminating different shades of green as represented in the set of colour charts.

4.3 Materials and Methods

4.3.1 Munsell standard colour charts

The Munsell Colour System is a colour space which pre-dates the more modern digital scheme but is still widely used as a standard to identify colours. Three attributes called Hue, Value and Chroma are used for the colour notation (http://munsell.com). Chromatic colours are divided into five principal classes which are given the Hue names red (R), yellow (Y), green (G), blue (B), and purple (P), along with five intermediate hues named yellow-red (YR), green-yellow (GY) and so on, and each hue is divided into ten steps. The Value notation indicates the degree of lightness or darkness of a colour and the Chroma notation indicates the strength or saturation. Any chromatic colour is written “Hue Value/Chroma” such as “2.5G 7/10”. *Munsell Colour Charts for Plant Tissues* (Gretag–Macbeth, New Winsor, NY, USA) is a specialised product for plant scientists working with growth rates, nutrient deficiencies, plant diseases and other plant processes. For example, Raese *et al*. (2007) determined the nutrient status in leaves for apple trees using Munsell Colour chips of 7.5GY, 5GY and 2.5GY as indicators of high, middle and low levels of nitrogen, respectively.

We used matte sheets (8.5 inch × 11 inch; X-Rite, Grand Rapids, MI, USA) for our experiments. Four colours were selected from the plant tissues charts to represent leaf growth stage of deciduous broad-leaved trees; dark green (7.5GY 4/4) for fully mature leaves, green (5GY 6/8) for newly expanded leaves, yellowish green (2.5GY 7/10) for emerging leaves and yellow (5Y 8/8) for senescent leaves (hereafter noted as M1_7.5GY, M2_5GY, M3_2.5GY and M4_5Y respectively). Sample photos of the matte sheets and the spectral reflectance measured by a single-beam field spectro-radiometer GER1500 (Geophysical and Environmental Research Corporation, Millbrook, NY USA) are shown in Figure 4.1.

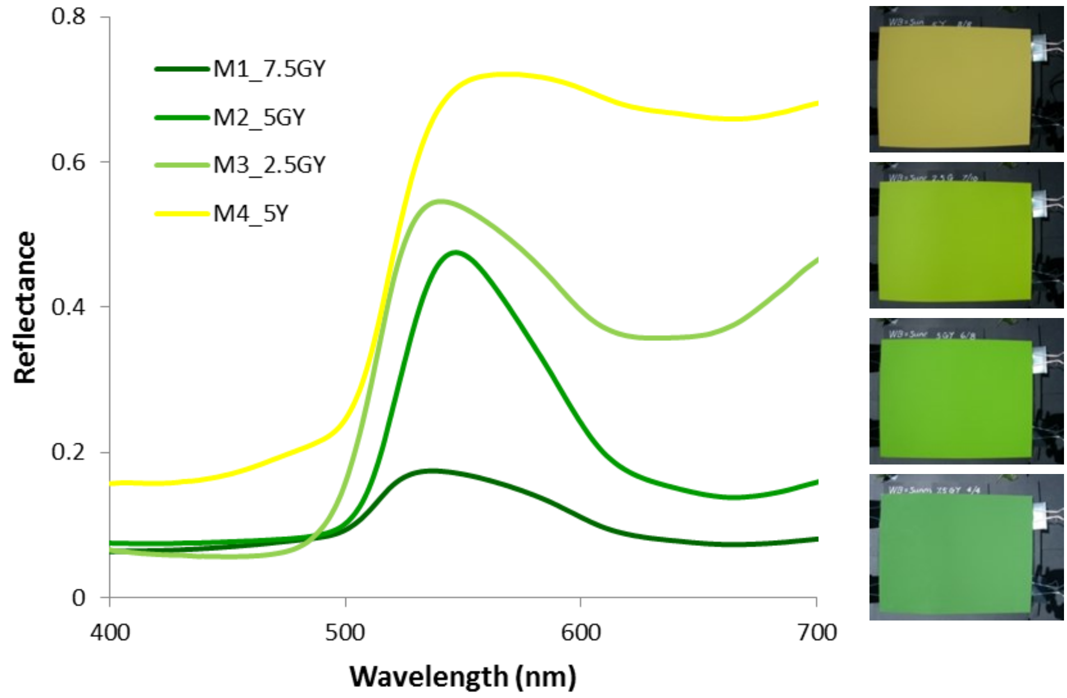

Figure 4.1 Spectral reflectance of four matte colour sheets and the sample photos. Four colours were chosen from Munsell Color Charts for Plant Tissues.

4.3.2 Digital photograph

The photographic experiments were carried out under open conditions in Bordeaux, France from 24th July to 1st August 2012. Two models of cameras were used for the experiment (Table 4.1); a commercial compact digital camera Coolpix 4500 (Nikon Corp., Tokyo, Japan; hereafter called Coolpix) and a surveillance live image camera, NetCam SC 5MP (StarDot Technologies, Buena Park, CA, USA; hereafter called NetCam). For Coolpix, exposure was set to *auto* and digital images were stored as compressed JPEG file with the resolution of 2272 × 1704 pixels, three channels of 8 bit RGB colour information, and a camera setting of *fine* image quality. White balance was set to *auto* and *fixed* for sunny conditions. For the NetCam, colour balance was set to *auto* and manually *fixed* with settings of red 256, green 180 and blue 256. Exposure was set to *auto* and image quality set to 1296 × 960 pixels, the highest possible for this model. Photographs were taken using two different cameras of each model (hereafter called lots) between the times of 11:00 and 17:00 Central

European Time at two conditions of illumination, i.e., when the sun was not obscured and when the sun was obscured. The Munsell matte sheets and the colour checker chart were placed on a table of 30 cm height and the pictures were taken from above, looking down vertically at the subject.

Table 4.1 Specification of cameras used in this study

	CoolPix	NetCam
Maker	Nikon Corp, Japan	StarDot Technologies, USA
Model	COOLPIX 4500	NetCam SC 5MP
Image sensor	CCD	CMOS
Lens focal length	7.85–32 mm	4–8mm
Image format and size	JPEG format 2272×1704 pixels	JPEG format 1296 × 960 pixels

4.3.3 Colour indices

ImageJ (National Institutes of Health, Bethesda, MD, USA; Version 1.42q) was used to extract red, green and blue (RGB) digital numbers from the images taken by the two models of camera. Rectangular areas in the middle of colour samples were defined as the region of interest for the analysis. We calculated the strength of a channel as the ratio of the digital numbers of the channel to the total digital numbers of the RGB channels (S_{red}, S_{green}, S_{blue}), Hue, Saturation and Lightness of the HSL colour scheme and Green Excess Index (equations are listed in Table 4.2; see also Mizunuma *et al.* (2011) for RGB and HSL colour system). To compare with the spectral measurements for the matte sheets (Figure 4.1), we used the band width for the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor; Band 1 for red (620 - 670 nm), Band 4 for green (545 - 565 nm) and Band 3 for blue (459 - 479 nm) respectively (R_{red}, R_{green}, R_{blue}) to calculated the same indices (Table 4.2). Statistical analysis was performed using Minitab 16 Statistics Software (Minitab Inc, State College, PA, USA).

Table 4.2 Colour indices used in this study.

Colour index	Formulation	Reference
Calculated from digital images		
Strength of red	$S_{red} = n_{red} / (n_{red} + n_{green} + n_{blue})$	Gillespie, Kahle & Walker (1987)
Strength of green	$S_{green} = n_{green} / (n_{red} + n_{green} + n_{blue})$	
Strength of blue	$S_{blue} = n_{blue} / (n_{red} + n_{green} + n_{blue})$	
Hue		Joblove & Greenberg (1978)
	$Hue = (b - r) / ((I_{max} - I_{min}) \times 60) + 120$ if $g = I_{max}$	
	$Hue = (r - g) / ((I_{max} - I_{min}) \times 60) + 240$ if $b = I_{max}$	
	$Hue = (g - b) / ((I_{max} - I_{min}) \times 60) + 360$ else if $g < b$	
	$Hue = (g - b) / ((I_{max} - I_{min}) \times 60)$ otherwise	
Lightness	$L = (I_{max} + I_{min}) / 2$	
Saturation	$S = (I_{max} - I_{min}) / (I_{max} + I_{min})$ if $L \leq 0.5$	
	$S = (I_{max} - I_{min}) / (2 - (I_{max} + I_{min}))$ if $L > 0.5$	
	$S = 0$ if $I_{max} = I_{min}$	
Green Excess Index	$GEI = 2 \times n_{green} / (n_{red} + n_{blue})$	Woebbecke *et al.* (1995)
Calculated from spectral reflectance		
Strength of red	$S_{red}\_R = R_{red} / (R_{red} + R_{green} + R_{blue})$	Gillespie, Kahle & Walker (1987)
Strength of green	$S_{green}\_R = R_{green} / (R_{red} + R_{green} + R_{blue})$	
Strength of blue	$S_{blue}\_R = R_{blue} / (R_{red} + R_{green} + R_{blue})$	
Hue		Joblove & Greenberg (1978)
	$Hue\_R = (R_{blue} - R_{red}) / ((R_{max} - R_{min}) \times 60) + 120$ if $R_{green} = R_{max}$	
	$Hue\_R = (R_{red} - R_{green}) / ((R_{max} - R_{min}) \times 60) + 240$ if $R_{blue} = R_{max}$	
	$Hue\_R = (R_{green} - R_{blue}) / ((R_{max} - R_{min}) \times 60) + 360$ else if $R_{green} < R_{blue}$	
	$Hue\_R = (R_{green} - R_{blue} / ((R_{max} - R_{min}) \times 60)$ otherwise	
Lightness	$L\_R = (R_{max} + R_{min}) / 2$	
Saturation	$S\_R = (R_{max} - R_{min}) / (R_{max} + R_{min})$ if $L \leq 0.5$	
	$S\_R = (R_{max} - R_{min}) / (2 - (R_{max} + R_{min}))$ if $L > 0.5$	
	$S\_R = 0$ if $R_{max} = R_{min}$	
Green Excess Index	$GEI\_R = 2 \times R_{green} / (R_{red} + R_{blue})$	Woebbecke *et al.* (1995)

The terms S_{red}, S_{green}, S_{blue} are chromatic co-ordinates *sensu* Gillespie, Kahle & Walker (1987); n_{red}, n_{green}, n_{blue} are the values of red, green and blue, respectively; R_{red}, R_{green}, R_{blue} are the spectral reflectance of red (620 - 670 nm), green (545 - 565 nm) and blue (459 - 479 nm) band respectively; $r = n_{red} / 255$, $g = n_{green} / 255$, $b = n_{blue} / 255$; I_{max} is maximum value of r, g and b and I_{min} is minimum value of r, g and b; R_{max} is maximum value of R_{red}, R_{green}, and R_{blue} and R_{min} is minimum value of R_{red}, R_{green}, and R_{blue}.

4.4 Results

4.4.1 Colour indices for Munsell matte sheets

The effects of varying sky conditions, balance settings of the cameras and camera model all influenced the indices (Figure 4.2, also cf., 4.S1, 4.S2, 4.S3 and 4.S4). In the case of S_{green} only weak differences were detected between the model leaves for the images taken by NetCam particularly with *auto* balance setting, even though they are so clearly different to the human eye (Figure 4.1). For Hue, on the other hand, there are very clear differences between the model leaves, showing a gradation from M1 to M4 throughout the various combinations. The variation between the indices was further explored using an analysis of variance (ANOVA) with four factors: matte sheets, camera models, balance settings and sky conditions (Table 4.3). The indices were separated into two groups: those indices most influenced by the camera model and those most influenced by the sheet. The results for S_{green} showed that camera model was the most important factor ($F=858.46$, $P<0.001$) followed by sheet ($F=135.54$, $P<0.001$) and balance setting ($F=134.10$, $P<0.001$), while sky condition has least impact on S_{green} ($F=10.65$, $P<0.01$). Camera model was also the strongest factor for N_{green} ($F=418.08$, $P<0.001$), N_{blue} ($F=199.68$, $P<0.001$), S_{blue} ($F=655.78$, $P<0.001$), Saturation ($F=758.56$, $P<0.001$) and GEI with the large F statistic values ($F=1333.56$, $P<0.001$). Meanwhile, the factor having the largest impact for Hue was sheet ($F=1166.18$, $P<0.001$) ahead of camera model ($F=69.81$, $P<0.001$) and sky condition ($F=26.54$, $P<0.001$), while balance setting was not significant ($F=1.61$, NS). The different sheets also had the most impact on N_{red} ($F=526.82$, $P<0.001$), S_{red} ($F=223.74$, $P<0.001$) and Lightness ($F=41.03$, $P<0.001$).

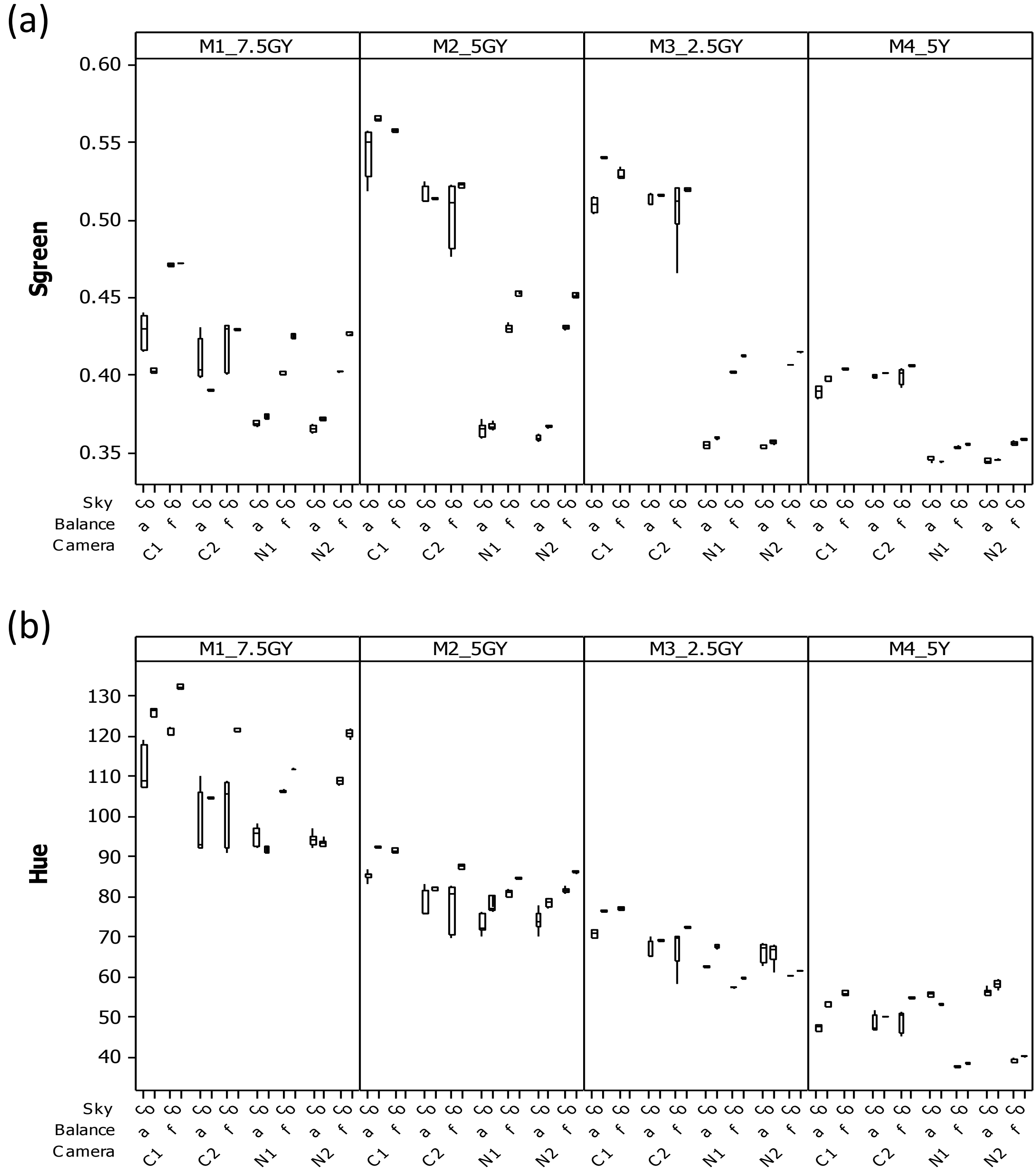

Figure 4.2 Effects of cameras (C1, C2: COOLPIX, N1, N2: NetCam), balance setting (a: auto, f: fixed or manual) and sky conditions (c: clear – sun not obscured, o: sun obscured) in four colours of Munsell matte sheets for (a) Strength of green and (b) Hue. The top and the bottom of each box indicate the third quartile (Q3) and the first quartile (Q1) respectively. The line in the box presents the median. The upper and the bottom whisker extends to the highest data value within the upper limit (Q3 + 1.5 (Q3 - Q1)) and the lower limit (Q1- 1.5 (Q3 - Q1)) respectively.

Table 4.3 Summary of the analysis of variance exploring four factors: Munsell matte sheets, camera models, balance settings of the camera and sky conditions.

	Matte sheet			Camera model			Balance setting			Sky conditions		
N_{red}	526.82	(92.2)	***	30.28	(1.8)	***	0.92	(0.1)	NS	103.15	(6.0)	***
N_{green}	87.95	(36.8)	***	418.08	(58.3)	***	0.38	(0.1)	NS	34.95	(4.9)	***
N_{blue}	25.88	(18.9)	***	199.68	(48.6)	***	122.72	(29.9)	***	10.85	(2.6)	**
S_{red}	223.74	(86.1)	***	57.18	(7.3)	***	47.47	(6.1)	***	4.08	(0.5)	*
S_{green}	135.54	(28.8)	***	858.46	(60.9)	***	134.10	(9.5)	***	10.65	(0.8)	**
S_{blue}	134.72	(32.9)	***	655.78	(53.3)	***	168.85	(13.7)	***	0.55	(0.0)	NS
Hue	1166.18	(97.3)	***	69.81	(1.9)	***	1.61	(0.0)	NS	26.54	(0.7)	***
Saturation	100.53	(24.2)	***	758.56	(60.9)	***	185.06	(14.9)	***	0.61	(0.0)	NS
Lightness	41.03	(64.9)	***	2.61	(1.4)	NS	36.87	(19.4)	***	27.00	(14.2)	***
GEI	162.22	(24.5)	***	1333.56	(67.0)	***	165.37	(8.3)	***	4.31	(0.2)	*

Data were analysed using a four-way ANOVA. The first numbers given are the F-values for the full ANOVA. The second number in brackets is the percentage of the explanatory model that is explained by that factor. NS not significant, *P<0.05, **P<0.01 and ***P<0.001.

4.4.2 Comparison of colour indices from images and reflectance

The colour indices derived from the spectral reflectance of the RGB bands for the four matte sheets were compared with the mean colour indices from digital images taken under the sunny conditions for the four separate cases: 1) Coolpix-*auto* balance, 2) Coolpix-*fixed* balance, 3) NetCam-*auto* balance and 4) NetCam -*fixed* balance. Digital number of red (N_{red}) showed good correlations with the reflectance of the red band (R_{red}) except the case of NetCam-*auto* (percentage of explained variance r^2 = 0.99, 0.99, 0.61 and 0.95 for the four cases respectively, Figure 4.3a). Conversely, N_{green} for CoolPix showed poor correlations with R_{green}, while N_{green} for NetCam was well correlated with R_{green} (r^2 = 0.05, 0.05, 0.85 and 0.90, Figure 4.3b). N_{blue} correlated poorly with R_{blue} except the case of NetCam-*fixed*, though the range of R_{blue} was limited to less than 0.2 (r^2 = 0.03, 0.04, 0.25 and 0.88, Figure 4.3c). The strength of red, green and blue for NetCam-*auto* was poorly related with those from reflectance in comparison with the other cases (r^2 for S_{red} = 0.78, 0.74, 0.33 and 0.83, r^2 for S_{green} = 0.81, 0.76, 0.30 and 0.86, r^2 for S_{blue} = 0.97, 0.97, 0.17 and 0.98, Figure

4.3d, e, f). Hue showed good correlations between images and reflectance for all combinations (r^2 = 0.93, 0.91, 0.87 and 0.96, Figure 4.3g). GEI from images showed poor correlations with GEI from reflectance for all cases (r^2 = 0.31, 0.24, <0.01 and 0.14, Figure 4.3i). The slopes of the correlations for Coolpix were similar across the two balance settings, while the slopes for NetCam showed a discrepancy between *auto* and *fixed* balance.

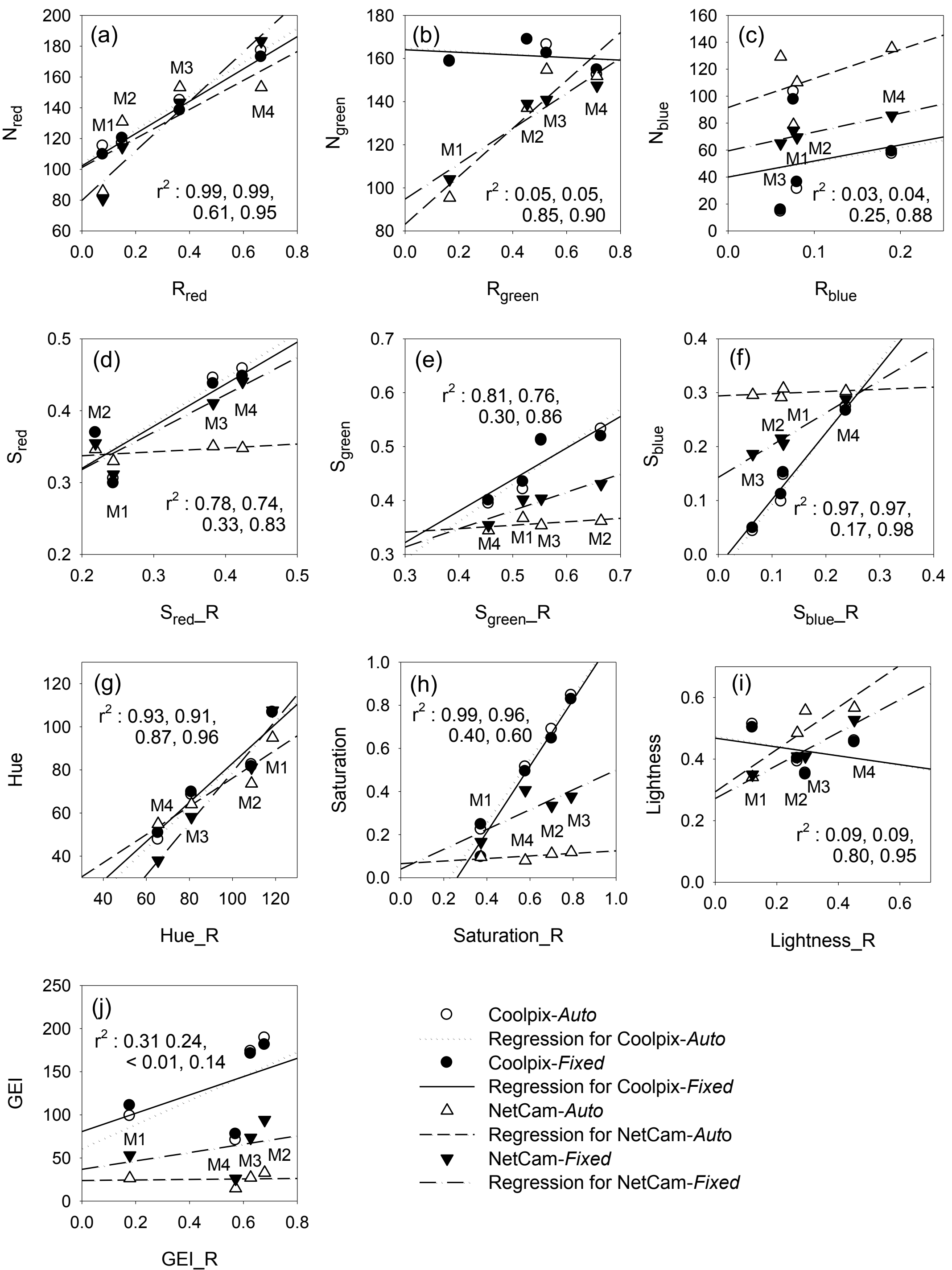

Figure 4.3 Comparison of colour indices for Munsell matte sheets from spectral reflectance with the mean from images taken under sunny sky conditions for four cases: 1) Coolpix-*auto* balance, 2) Coolpix-*fixed* balance, 3) NetCam-*auto* balance, and 4) NetCam-*fixed* balance. N_{red}, N_{green}, N_{blue} are the digital number of red, green and blue. R_{red}, R_{green}, R_{blue} are the spectral reflectance of red (620 - 670 nm), green (545 - 565 nm) and blue (459 - 479 nm) band. The four reported values of r^2 refer to the Matte sheets M1, M2, M3 and M4, respectively.

4.5 Discussion

4.5.1 Using colour indices to distinguish leaf colour

Leaf colour charts are widely used as an inexpensive practical tool to diagnose the nitrogen status of crops (Lemaire, Jeuffroy & Gastal 2008). In the present study, we took pictures of colour sheets selected from the *Munsell Colour Chart for Plant Tissues*, using the coloured sheets as model leaves, to determine which colour index is most able to detect the gradation of leaf colour that occurs throughout a season. Attempts have been made to show how leaf colour evolves over the season. For example, Gond *et al*. (1999) simulated absorptance, transmittance and reflectance for pedunculate oak (*Quercus robur* L.) at the leaf scale using the PROSPECT model (Jacquemoud & Baret 1990) with chlorophyll concentration and water content measured throughout a growing season as the state variables. After a rapid increase in May, the chlorophyll concentration reached a maximum in August followed by a progressive decline from October until leaf fall in November. High chlorophyll concentration in summer caused high absorptance in the green band in the model simulation and consequently a lower reflectance than in spring, although the reflectance in the green band remained higher than the reflectance in the red and blue bands. This induces a change in leaf colour to dark green in summer. *In situ* leaf reflectance measurements of paper birch (*Betula papyrifera* Marsh.) across a range of chlorophyll concentration showed similar reflectance curves to the PROSPECT simulation (Richardson, Duigan & Berlyn 2002). The shades of green that we employed are similar to those shades observed in leaves which have different concentration of chlorophyll. This is well demonstrated by the comparison of the reflectance spectra from M1 to M4 matte sheets (Figure 4.1) with the reflectance spectra of leaves (Richardson, Duigan & Berlyn, 2002, Figure 4.2 in their paper). Although paper sheets cannot express water contents or thickness in leaves, the approximation to the reflectance spectrum of leaves seems sufficient to explore the visible range of reflectance for single leaves.

The relationship between reflectance in RGB bands from a radiometer and RGB digital numbers from cameras was not straightforward. Digital number of red

(N_{red}) has a good correlation with the reflection of red band (R_{red}) across the camera models and the balance setting, while the relationship between N_{green} and R_{green} differed depending on the camera models. N_{green} from NetCam showed a good correlation with R_{green}, by contrast, N_{green} from Coolpix took higher values than N_{green} from NetCam and correlated poorly with R_{green}. Although the reflection of blue band (R_{blue}) for three sheets was are very similar, the digital number varied widely. The discrepancy may be caused by the sensitivity of image sensors particularly for the green band. The normalisation using the ratio of each channel to the total RGB channels contributed to improve the correlation in green and blue channel for Coolpix, while the comparison for Netcam showed poorer correlation when *auto* balance was selected. Although R_{green} decreases with the increase of chlorophyll concentration, S_{green} does not show such a negative dependency. This may explain the observation that S_{green} does not decrease rapidly in the autumn in previous *in situ* studies for 'turn-to-yellow' species (Ahrends *et al.* 2009; Mizunuma *et al.* 2013). In agreement with a previous study (Saitoh *et al.* 2012), Hue from images showed a good correlation with Hue from reflectance across camera models and balance settings. Hue conversion looks useful to minimise the influence of camera factors. On the other hand, the relation of Green Excess Index (GEI) between image and reflectance was weak in all cases. This index seems to emphasise the discrepancy between reflectance and digital number.

4.5.2 What is the preferred colour index for detecting differences between leaves?

In terms of factors which influence colour of images, we tested different models of camera, different lots (*i.e.,* different individual cameras of the same model), different colour balance settings and we took pictures under different sky conditions using the same downward looking view. As expected, differences in colour indices between lots were much smaller than differences between the models: *i.e.,* a commercial digital camera, Coolpix and a live image camera, NetCam. Although variations in colour indices under sunny conditions were generally larger than variations under overcast conditions, the differences observed across models were much greater than the differences caused by changes in sky conditions. The differences caused by changes in white balance setting were small for images taken by Coolpix, while the indices from images taken by Netcam were significantly influenced by the colour settings, as has been reported in previous *in situ* monitoring of canopies (Richardson *et al.* 2009; Mizunuma *et al.* 2013). The results of analysis of variance which compared the differences between factors of matte sheets, camera models, balance setting and sky conditions revealed that GEI, Saturation, S_{green}, S_{blue}, N_{green} and N_{blue} were primarily influenced by camera models rather than by the different colours of the matte sheets. The impact for GEI, Saturation, S_{green}, and S_{blue} were strong, and it was amplified through the conversion using primitive N_{green} and N_{blue}. On the other hand, Hue was the most sensitive index to discriminate leaf colours with only a small impact caused by the other factors, followed by N_{red} and S_{red}. Hue, N_{red} and S_{red} also had good correlations with those derived from reflectance, though N_{red} and S_{red} from images taken by NetCam with *auto* balance showed a lower percent of explained variance (r^2 was 0.61 and 0.33 respectively). As shown in two previous studies (Graham *et al.* 2009; Mizunuma *et al.* 2013), these results suggest that Hue is less susceptible to any difference in optical properties of cameras by separating out the degree of Saturation. Hue values were stable not only for different cameras (a compact digital camera or a surveillance live image camera) but also for different optical instruments (a camera and a spectro-radiometer). The fact that the range of values from cameras was the same as the range from a calibrated spectro-radiometer provides some support for the hypothesis that Hue is a sensitive colour index for phenological studies using digital images.

Although our camera experiments carried out under relatively controlled conditions underlined the difference in sensitivity between colour indices, the method is empirical. Although it is difficult to measure absolute values, the relative sensitivity of RGB sensors in camera systems can be derived by measuring the radiative intensity and the digital numbers using monochromatic light generated at different wavelength (Nakaji, personal communication). The approach may solve issues of camera calibration and could be useful to evaluate long-term degradation of camera system. Furthermore, information on sensor sensitivity may allow simulating colour indices from digital photographs using leaf reflectance for different species and in different seasons, which will contribute to revealing performance of colour indices.

For real leaves the pattern of spectral reflectance shows a sharp increase between 680 nm to 730 nm. This transition, called the red-edges, characterise green vegetation from other natural surfaces and is used for vegetation indices such as the Normalised Difference Vegetation Index (NDVI, Tucker 1979). Since the reflectance in near infrared (NIR) region relates to absorption of water, the index is useful to monitor vegetation stress. Although infrared light is cut off by a filter and does not reach image sensors in camera system, sensors have sensitivity to the near infrared region. Some studies have employed a modified camera replacing an NIR-cut filter with NIR band-pass filter together with a standard camera to monitor development of crops (Shibayama *et al.* 2009; Sakamoto *et al.* 2012). A commercially available multichannel camera (ADC3, Teracam Inc., U.S.A) has been used to observe the seasonal change in NDVI for six tree species in comparison with the chlorophyll content (Nakaji, Oguma & Hiura 2011). Recently Phenocam network has employed Netcam SC IR (StarDot Technologies) which has one IR channel in addition to RGB channels (Richardson *et al.* 2013). Further studies using vegetation indices from multichannel cameras could identify advantages and limitations of using colour indices from conventional RGB cameras.

4.6 Conclusions

Camera tests designed to investigate the resolving power of different colour indices were carried out under sunny and overcast sky conditions and using different camera settings. The targets were standard colour sheets chosen to represent model leaves at different growing stages, whose reflectance in RGB bands was also measured. Colour indices based on green were strongly influenced by camera models, while red-based indices were little affected by different models. S_{green} is often used to quantify greenness of forest canopy with the advantage of detecting high values for young leaves. However, S_{green} for yellow-coloured leaves took similar values with fully mature leaves, which suggests that S_{green} was not sufficiently sensitive to identify, for example, the decrease of chlorophyll in autumn. On the other hand, Hue distinguished leaf colour samples with little influence of the specific model of camera, colour balance setting or sky conditions and showed a good correlation with Hue derived from spectral reflectance. Among the colour indices tested, Hue was the most useful to detect differences between leaves of different colours at different stage of development.

4.7 Acknowledgements

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4.9 Supporting Information

Additional supporting information was prepared for online access.

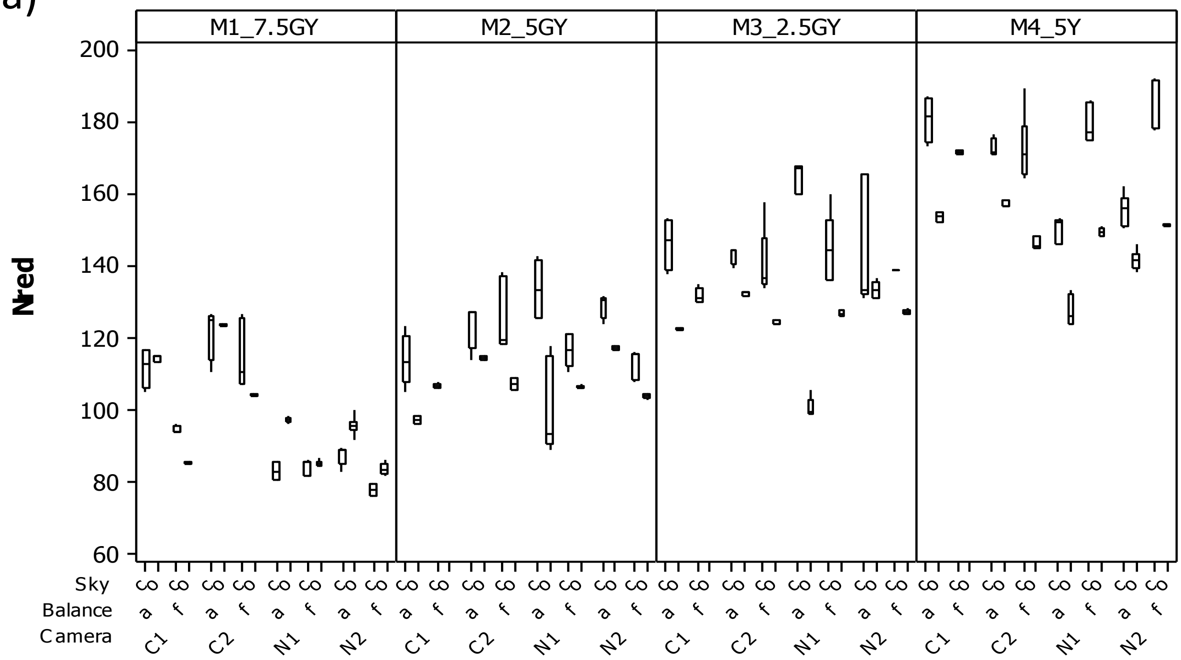
Figure 4.S1 As Figure 4.3 but for (a) N_{red} and (b) N_{green}.

Figure 4.S2 As Figure 4.3 but for (a) N_{blue} and (b) GEI.

Figure 4.S3 As Figure 4.3 but for (a) S_{red} and (b) S_{blue}.

Figure 4.S4 As Figure 4.3 but for (a) Saturation and (b) Lightness.

(a)



(b)

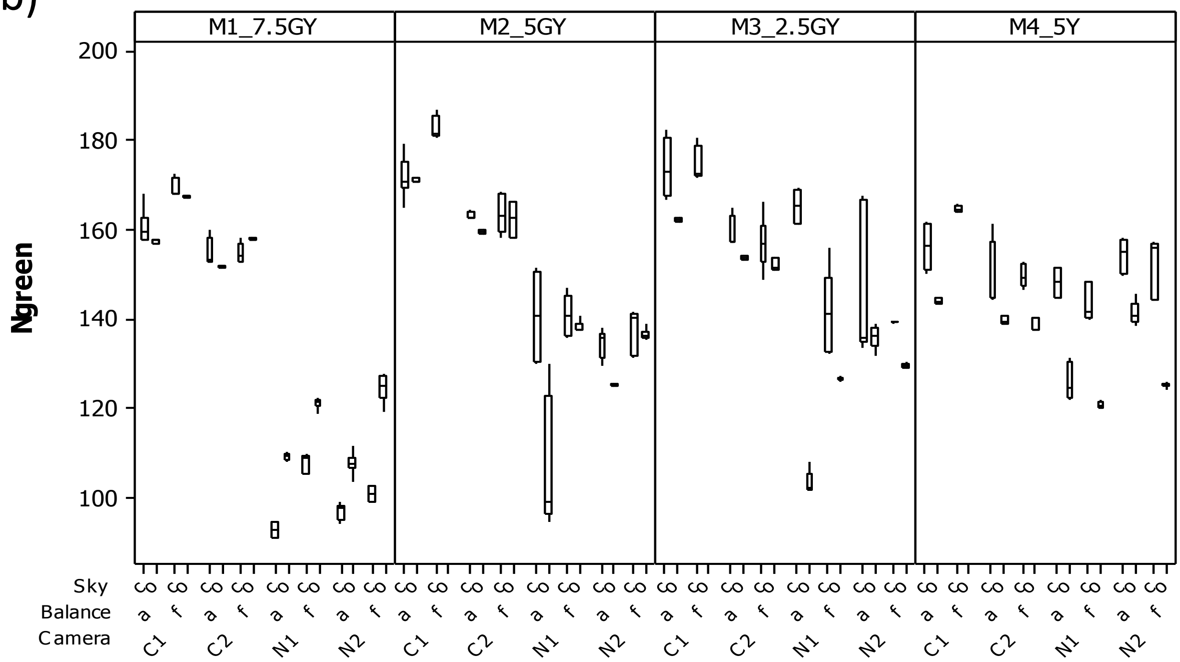


Figure 4.S1 As Figure 4.3 but for (a) N_{red} and (b) N_{green}.

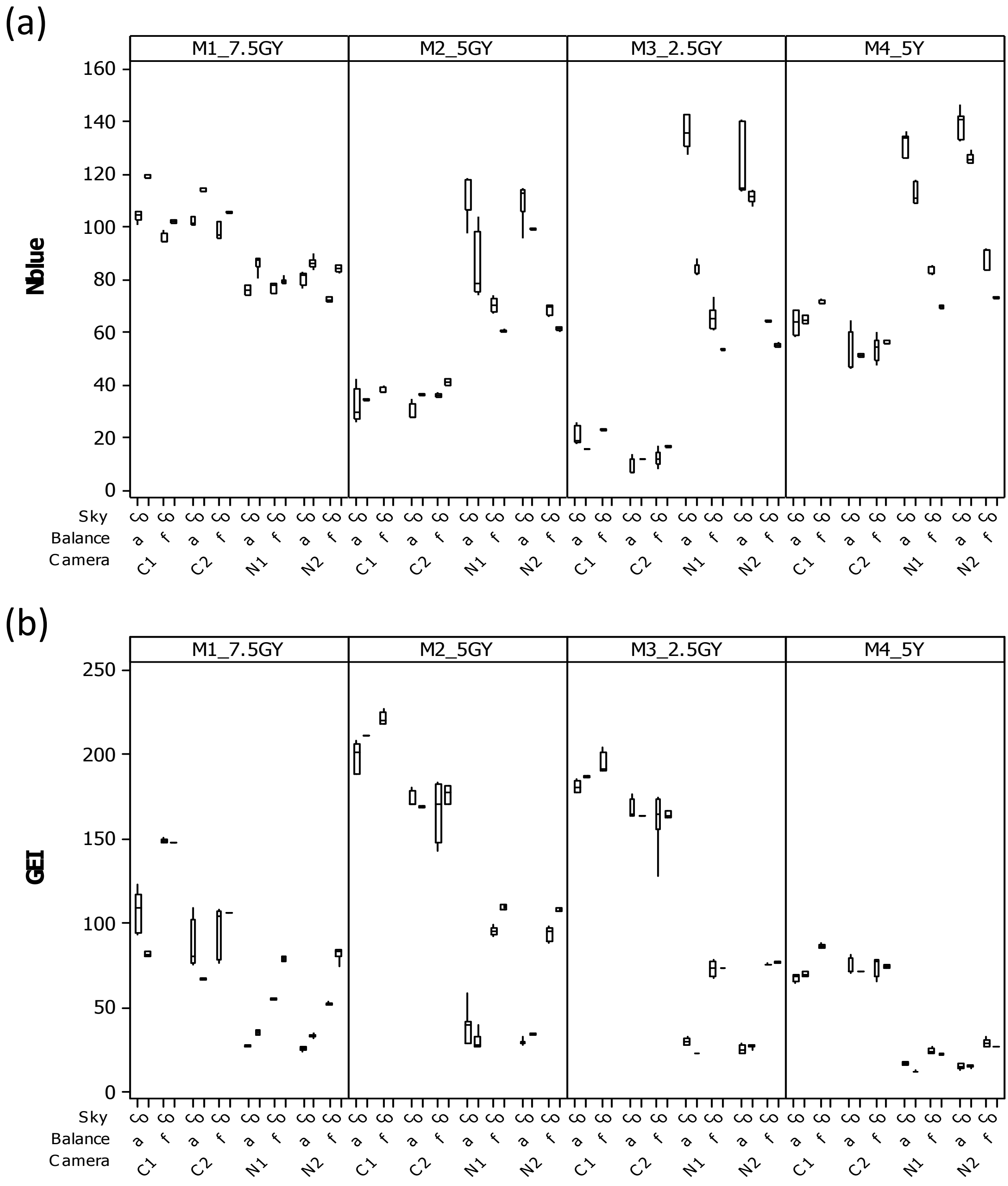


Figure 4.S2 As Figure 4.3 but for (a) N_{blue} and (b) GEI.

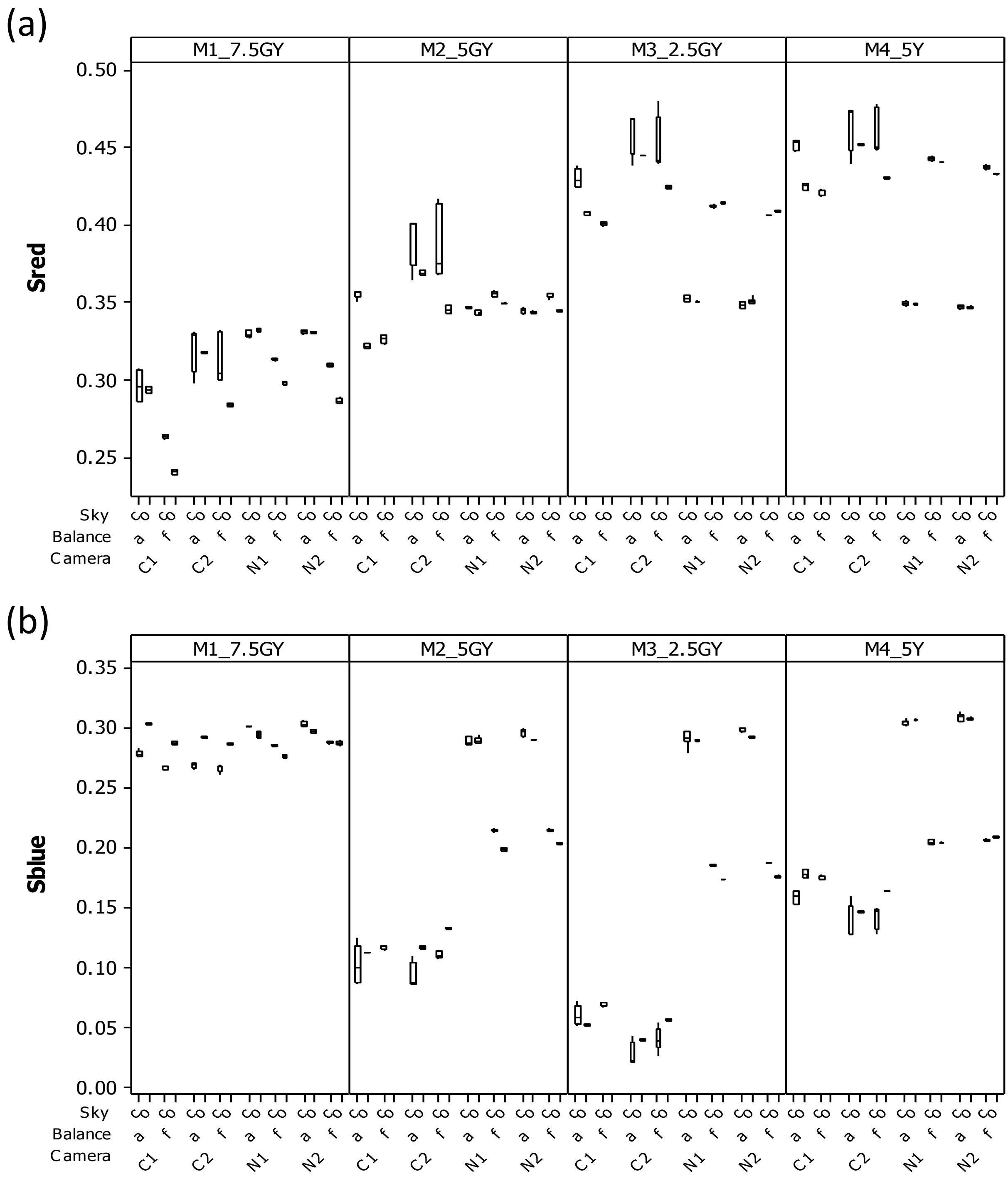


Figure 4.S3 As Figure 4.3 but for (a) S_{red} and (b) S_{blue}.

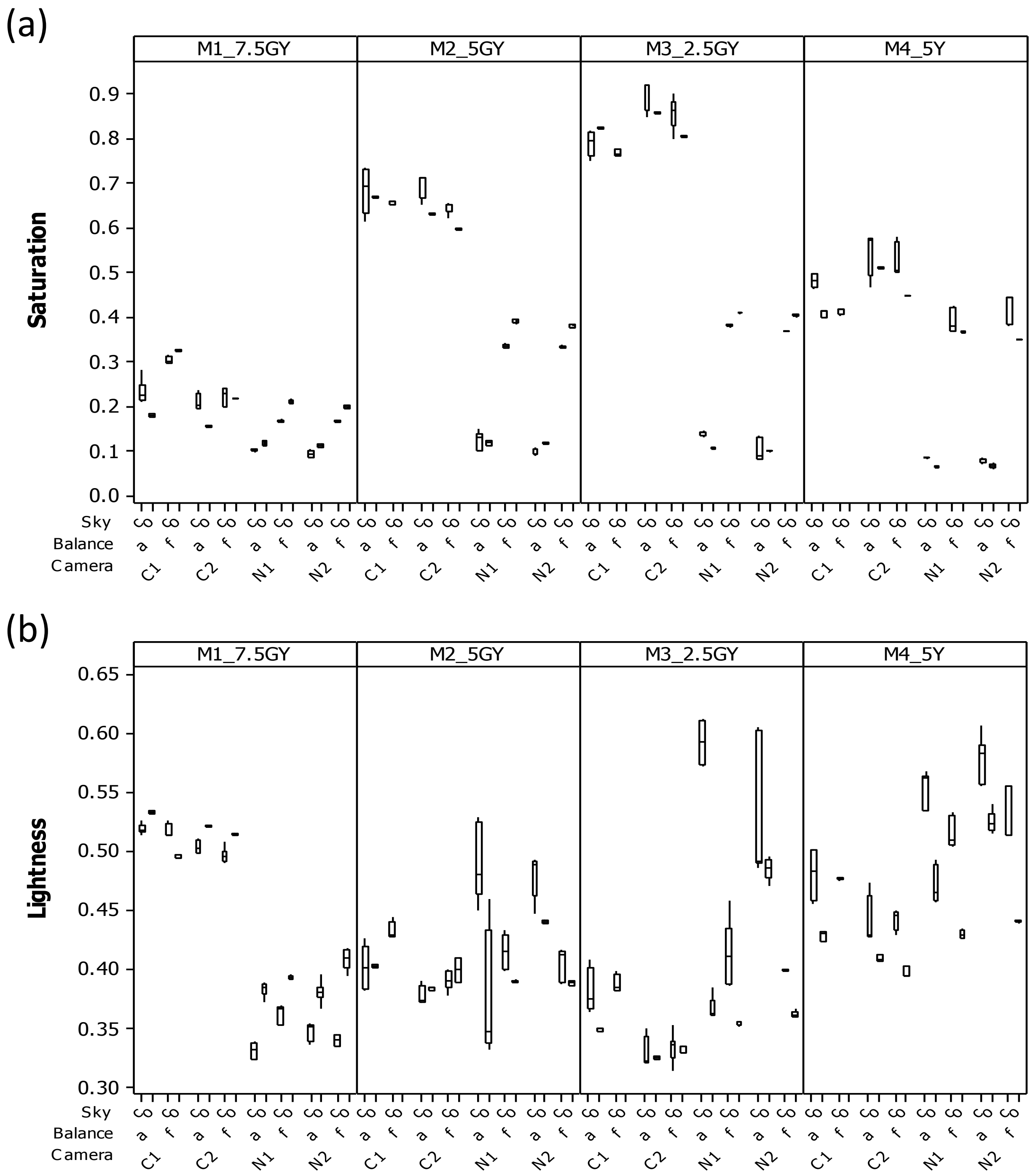


Figure 4.S4 As Figure 4.3 but for (a) Saturation and (b) Lightness.

Chapter 5

General Discussion, Conclusions and Recommendations

5 General Discussion, Conclusions and Recommendations

5.1 Observing forest phenology using camera systems

The key questions for the present study are: (i) can digital images detect phenological changes in deciduous trees, (ii) what is the optimal colour index for recording canopy phenology, (iii) do changes in digital images relate to changes in CO_2 fluxes from deciduous canopies? In order to address the questions a pilot study was undertaken using images of a beech forest to try and identify the most effective colour indices (**Paper I**). This was followed by an analysis of images of an oak-dominated forest taken by two camera systems to examine the relationship between forest colour and carbon uptake (**Paper II**). Finally, a set of standard charts was used to simulate model leaves in order to determine the robustness of the various colour indices (**Paper III**).

5.1.1 Digital images as a tool for the monitoring of forest phenology

Digital imaging has advanced rapidly in the last twenty years; cameras and webcams are now cheap and they provide high quality images at relatively low cost. As a result, the use of digital cameras for forest monitoring has been developing rapidly (Vilhar *et al.* 2013). Cameras installed in deciduous forests are expected to enable monitoring of tree phenology with a high frequency and much less manual input than traditional approaches. To examine how remotely recorded images might be used for the interpretation of key phenological stages, one-year-long images of a beech forest with a horizontal view (**Paper I**) and two-year-long images of an oak-dominated forest with both a horizontal view and a downward view were used (**Paper II**). The images, taken every 30 minutes, showed the detail of seasonal changes in trees at high frequency, particularly when buds broke and leaves expanded in the spring. The number of trees that can be observed manually is limited due to accessibility and labour costs, while the images provided a wide range of trees in the side field of view, showing different timings between tree species, individual trees of the same species, and trees at different locations. Tree tops in side-view images in the oak forest facilitated the determination of standard flushing stages, like those manually undertaken using a picture guide (Broadmeadow *et al.* 2000). Permanent photographic records also permit a thorough manual inspection to avoid any bias by observers in different years. Secondary flushing known as Lammas growth was observed on the oak canopy in summer coinciding with high air temperatures. An infection with oak mildew was clearly seen on leaves for some oak trees. Continuous observation using digital images helps to detect biotic and abiotic stress phenomena that are important indicators for responses of trees to climate change, as future warming may increase the occurrence of pest and diseases as well as changing phenological patterns. Moreover, a camera mounted above the canopy and facing downward provided an observation of understory growth prior to canopy growth, which influenced the start of carbon uptake in deciduous forests.

In addition to qualitative inspection, digital numbers extracted from the images were quantitatively analysed using time courses of colour indices (**Paper I, II**). The technique pioneered by Richardson *et al.* (2007) has been widely tested in temperate deciduous forests, evergreen forests and grassland (Richardson *et al.* 2007; Ahrends *et al.* 2008; Crimmins & Crimmins 2008; Ahrends *et al.* 2009; Jacobs *et al.* 2009; Richardson *et al.* 2009; Graham *et al.* 2010; Ide & Oguma 2010; Migliavacca *et al.* 2011; Nagai *et al.* 2011; Saitoh *et al.* 2012; Sonnentag *et al.* 2012). At sites with deciduous trees, the timings of an increase and decrease of green indices coincided with the timings of leaf onset and leaf fall respectively, and the phenological dates agreed well with the dates obtained by visual inspection of the images (Ahrends *et al.* 2009, **Paper I**). A test using 11 different cameras in a deciduous forest showed that the trends in colour indices were similar, although the RGB values from different images were different (Sonnentag *et al.* 2012). However, the angles of all cameras gave only horizontal views. We tested an outdoor surveillance camera with a near-horizontal view against a commercial 'fisheye' digital camera with a downward view, and we found that the time courses for the same trees were very similar between the two different view angles (**Paper II**). Because of ground vegetation development, which is not visible in the horizontal view, the greening-up date assessed from the downward images was ~5 days earlier than from the horizontal-view images. Changes in the setting of the camera's white balance substantially affected the values of the colour indices particularly for the images taken by outdoor cameras (Richardson *et al.* 2009, **Paper II**).

5.1.2 Using colour indices to observe forest phenology

As they absorb most of the energy in red and blue and reflect green, leaves look green to the human eye. Therefore, indices based on the colour green are intuitively appealing. However, do green indices provide the best way to observe forest phenology? As a variety of vegetation indices using different bands of spectral reflectance have been suggested from remote sensing (Huete *et al.* 1997; Huete *et al.* 2002), researchers using images have used not only green indices but also other indices to observe the seasonal changes of vegetation. The strength of green relative to the total of red, green and blue or chromatic coordinate of green (Richardson *et al.* 2007; Ahrends *et al.* 2008; Ahrends *et al.* 2009; Jacobs *et al.* 2009; Richardson *et al.* 2009; Migliavacca *et al.* 2011; Nagai *et al.* 2011; Hufkens *et al.* 2012; Saitoh *et al.* 2012; Sonnentag *et al.* 2012) and Green Excess Index or 2G_RB (Woebbecke *et al.* 1995), which emphasises the difference between green and red/blue, has also been widely used (Richardson *et al.* 2007; Crimmins & Crimmins 2008; Richardson *et al.* 2009; Graham *et al.* 2010; Ide & Oguma 2010; Migliavacca *et al.* 2011; Nagai *et al.* 2011; Saitoh *et al.* 2012; Sonnentag *et al.* 2012). These green indices are robust in relation to the strengths of red and strengths of blue, even using surveillance cameras with *auto* colour balance setting. When leaves emerged in spring, these green indices showed a sharp increase. This distinctive signal has been used to determine the timing of the spring green-up. However, the camera test using model leaves representing different growth stages revealed paradoxically that the green index decreases with the maturity of leaf (**Paper III**). In addition the *in situ* leaf reflectance measurements across a range of chlorophyll concentration also showed that the brightness of green decreases with the increase in chlorophyll (Richardson, Duigan & Berlyn 2002). A peak of the green indices could be used to infer a peak in leaf expansion, but does not seem to indicate a peak of chlorophyll development. In satellite remote sensing, Normalised Difference Vegetation Index (NDVI, Tucker 1979) is commonly used to estimate green-up dates. The vegetation index derived from the differences between reflectance in the red and in near-infrared regions indicates absorption by photosynthetic pigments. It is therefore important to appreciate that any greening-up which has been inferred from green indices and greening-up inferred from NDVI may represent somewhat different traits. Moreover, the strength of green was insensitive to leaf colour changing from green into yellow (**Paper III**), which makes detection of senescence in autumn difficult. Meanwhile, the strength of red or chromatic coordinates of red showed another distinctive peak in autumn in particular for species with leaves that turn to red or yellow (Richardson *et al.* 2009, **Paper I, II**). Despite the common practices developed from metrics based on remote sensing, a spring peak in the green index and an autumn peak in the red index could be good phenological indicators for any observing system using cameras.

Graham *et al.* (2009) suggested using an alternative colour system based on the Hue, Saturation and Light (HSL, Smith (1978), see 1.2.3) to estimate the increase in leaf area from digital images. Separated from the information about illumination, Hue could deal with colour in images containing both sunlit and shaded regions (Liu & Moore 1990). Hue could also be used to detect leaf flushing, showing much less scatter during the vegetative period than other vegetation indices (**Paper I**) and the metric was robust with respect to different types of cameras and under different sky conditions (**Paper II**, **III**). Agreeing with recent *in situ* measurements (Saitoh *et al.* 2012), our experiments demonstrated that camera-based Hue was correlated well with a spectro-radiometer-based Hue (reading from reflectance wavebands matching those of MODIS, **Paper III**).

A drawback of this study is a lack of statistical analysis to determine phenological dates (**Paper I, II**). Some studies employed curve fitting method using sigmoid functions to determine dates for start and end of on-set, start and end of senescence (Richardson *et al.* 2009) and some researchers calculated first and second derivatives to acquire the date of maximum green-up (Ahrends *et al.* 2008; Ide & Oguma 2010).

Bayesian analysis has been also used to find change points for phenological events (Henneken *et al.* 2013). If phenological dates were determined not by manual graph reading but by a statistical method, the optimal colour indices in **Paper I** might be differently concluded. Recently released MODIS product, Land Cover Dynamics or Global Vegetation Phenology (MCD12Q2; Ganguly *et al.* 2010) based on logistic functions fit to time series of the Enhanced Vegetation Index (EVI; Huete *et al.* 2002) provides the dates for onset the greenness increase ('green up'), onset greenness maximum ('maturity'), onset greenness decrease ('senescence'), and onset greenness minimum ('dormancy'). Applying such a statistical method could contribute to tracking dates of phenological event in an objective manner and comparing with metrics from space-borne remote sensing.

5.1.3 Relationship between carbon dioxide uptake and canopy colour

Carbon flux measurements using the eddy covariance method have helped researchers to develop models of ecosystem carbon balance. However, making reliable predictions of carbon fluxes is difficult due to phenological changes and possible abiotic/biotic stresses. Thus, camera systems at flux sites are desirable as monitors of canopy status (Baldocchi *et al.* 2005). The effects of late air frosts, which can lead to reductions in productivity, were evident in the canopy greenness, and also revealed different responses between species (Hufkens *et al.* 2012) and individual tree crowns (**Paper II**).

In agreement with previous studies (e.g. Richardson *et al*. 2009, Ahrends *et al*. 2009), the timing of the spring rise and autumn decline in CO_2 uptake approximately followed the seasonal pattern of strength of the green channel and Hue, suggesting that indices based on these attributes could be used to estimate the carbon uptake period (**Paper II**). Comparing the seasonal courses of carbon flux with the strength of the green channel, at some study sites, the peaks of green coincided with GPP peaks (Ide *et al.* 2011; Migliavacca *et al.* 2011) while at other sites, GPP lagged behind the peak of green (e.g., Ahrends *et al*. 2009; **Paper II**). The results at the former sites may be due to a short lag by a rapid growth of leaves. Meanwhile, Hue showed a gradual increase during the summer but then stabilised until the autumn colour developed.

Eddy covariance measurements are expensive in terms of equipment and skills needed to maintain the system and analyse the data. In addition to the high cost, they require certain criteria for location (Baldocchi 2003), and therefore the number of flux sites are limited. Remote sensing has an advantage for up-scaling using observations from satellites and aircraft and the cost efficiency has led to an increase in ground-observation stations (Gamon *et al.* 2010). In order to estimate carbon fixation from remotely-sensed data, the Light Use Efficiency (LUE) approach has frequently been used. This approach expresses GPP as the product of the Photosynthetically Active Radiation (PAR), the Fraction of PAR being absorbed by the plant canopy (FPAR) and the efficiency to convert absorbed radiation into biomass (Hilker *et al.* 2008). As metrics for FPAR, a numbers of vegetation indices have been suggested that use reflectance in different wavebands. For example, Normalised Difference Vegetation Index (NDVI), proposed many years ago following the launch of Landsat in 1972, derived from the differences between reflectance in the red region and in the near-infrared region (Tucker 1979), is still in wide use as a metric for vegetation greenness (Myneni *et al.* 1997; Zhou *et al.* 2001; Stockli & Vidale 2004). In the present study (**Paper II**), we tested whether colour indices derived from digital images can provide a useful metric for FPAR using a LUE model used for the MODIS product of vegetation production (Heinsch *et al.* 2003). Reflecting the different peak timings, the modelled GPP using the green index showed poor correspondence with the measured GPP, while the modelled GPP using Hue showed the best correlation, suggesting Hue could be used to predict carbon uptake. Further research at other sites and/or in other years is needed to explore whether such good relationships always exist.

5.2 Considerations for observation using cameras

5.2.1 Limitation of cameras

Some researchers have criticised the quantitative analyses of digital images on the grounds that cameras are '*not calibrated instruments*'. In fact most manufacturers do not allow the sensitivity and other characteristics of their image sensors to be known to the public for commercial reasons. Raw signals from sensors are manipulated to yield better looking photographs using selected algorithms. Calibration challenges also arise from camera degradation over time. For detecting phenological changes, calibration panels have been proposed as a solution to take account of different light conditions, but all calibration panels can saturate under bright light (Ahrends *et al.* 2009). A partial solution to avoid the manufacturers' conversion of signals to image is to use the raw format of image files. However, raw formats are available only in the high-end range (expensive) cameras and graphic tools which support raw formats are limited. Another solution could be to measure sensor sensitivity using monochromatic light generated in different wavelength. If you measure radiative intensity of each light and compare with digital numbers of images for the light, relative sensitivity of RGB sensors could be derived (Nakaji, personal communication). This requires a well-equipped laboratory which has a properly-maintained standard lamp. The approach may solve issues of camera calibration and aid long-term degradation issues. Despite such drawbacks, all recent research suggests that the use of colour indices derived from digital images is useful for detecting phenological events, even without calibration panels and with the use of compressed jpeg format files.

Angular sampling effects are also an additional source of unwanted variation. In remote sensing, the bi-directional reflectance distribution functions (BRDF) are applied to satellite observations to adjust for angular effects (Drolet *et al.* 2008; Quaife & Lewis 2010). Similar techniques could be applied to digital images, though it is doubtful whether scrupulous BRDF corrections can be effective on images from non-calibrated cameras.

5.2.2 Interpretation of colour indices

Our results indicate that Hue has good relationships with carbon uptake (**Paper II**) and is robust for different weather conditions and cameras (**Paper I**, **III**). But, what exactly does Hue or any other colour index mean? Figure 5.1 shows the factors that potentially influence image colour. Even if the factors related to illumination and cameras are excluded, there remain many sources of variability related to tree physiological processes. Key processes which are believed to be important are (i) the structure of the canopies, (ii) the chlorophyll content of leaves and (iii) maturation and condition of the leaf cuticle. Further work will be required to fully understand how changes in image colour relate to these factors and ultimately to the physiological activity. A comprehensive study using camera systems, spectroscopy and pigment analysis may help to develop a model to estimate colour components of images covering the different possible status of leaves. To separate the two processes of leaf area expansion and of change in leaf and pigment properties, analyses of each pixel using a colour threshold could be useful (Graham *et al.* 2009; Liang, Schwartz & Fei 2012), though the approach may be too complex to track phenology practically.

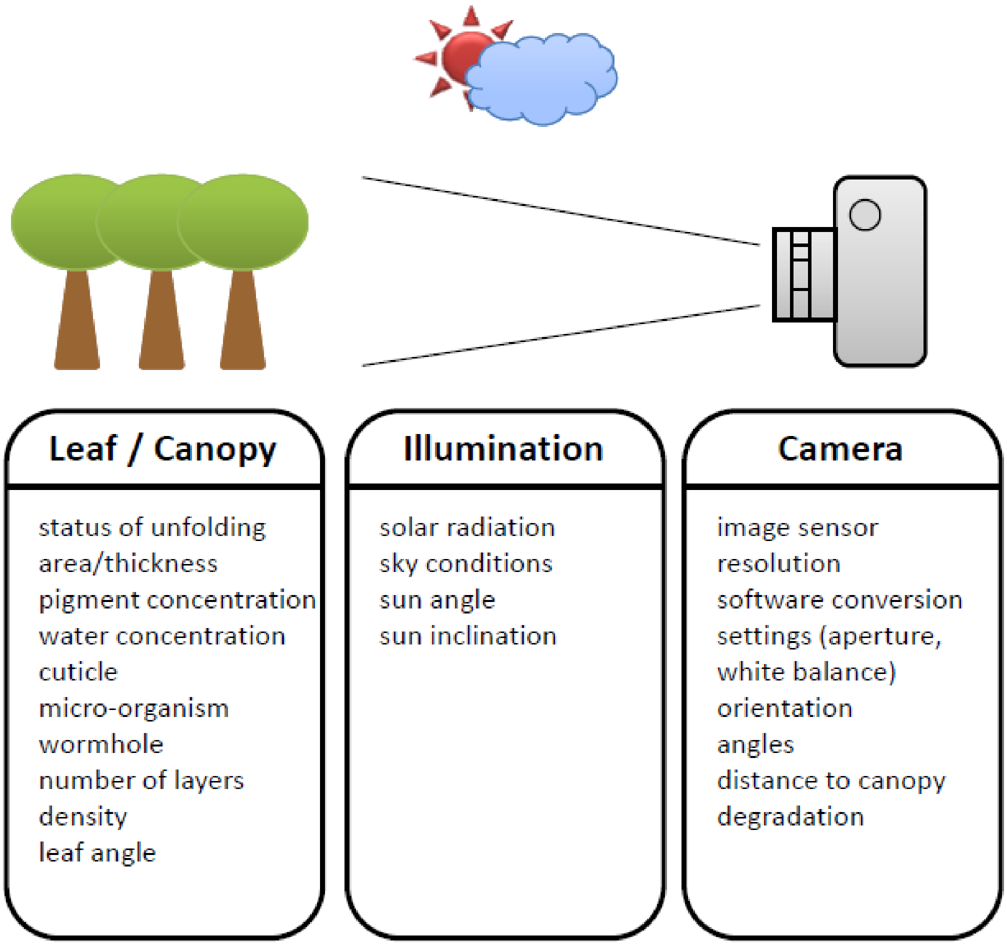


Figure 5.1 Factors influencing image colour

5.2.3 Future study using camera system

Thanks to the low cost and the ease of installation and maintenance, the use of digital cameras for monitoring forests is rapidly increasing (Vilhar *et al.* 2013). Long-term observation in flux monitoring sits could contribute to better understanding of how forests respond to future climate change. As well as the visual evidence of bud break or disease outbreak, RGB signals from digital images allow us to track vegetative phenology in a qualitative manner. However, the infrared cut-off filter assembled with the camera lens blocked the vital information from the infrared region such as absorption by water, which could be useful to detect water stress. Recently developed multichannel cameras provide an infrared channel as well as conventional

RGB channels which allow the user to calculate an NDVI-like index (Nakaji, Oguma & Hiura 2011; Richardson, Klosterman & Toomey 2013). The issues of calibration and degradation still remain for multichannel cameras. In terms of research equipment, it is desirable for multichannel camera makers to provide sensitivity of image sensors and calibration service (if they do not, then researchers will develop in-house facilities of their own) Once reliable multichannel cameras are available at a reasonable cost, they will be widely employed to study vegetative states in detail for example, between individual trees, between different species, between understory and canopy and even between shaded leaves and sun leaves.

"Citizen science" suggested by Irwin (1995) has spread into biology and ecology within two decades. The data collected by volunteers through the internet has been applied to study phenology, for example, first flowering (Amano *et al.* 2010) and bird migration (Hurlbert & Liang 2012). Of particular interest is use of mobile photo system. Observers can send photos from mobile phones and the images are stored in a central database tagged with the information of time and location. This reporting method avoids subjective bias by voluntary observers and provides accurate records, though the data availability may depends on population of volunteers. In addition to images from public cameras, images taken by volunteers will become an important resource for the future research. Images from the general public will help not only to track phenology but also to detect abnormal changes caused by biotic and abiotic stresses due to climate change.

5.3 Conclusions and recommendations

In order to examine the usefulness of cameras to observe seasonal changes in deciduous forests, we analysed canopy images and carried out a camera test using model leaves. The main findings of this study are:

- The time courses of colour indices derived from images taken in deciduous forests showed typical patterns throughout the growing season. Although cameras are not calibrated instruments, analyses of images permitted detection of phenological events such as leaf onset and leaf fall.

- The strength of the green channel (or the chromatic coordinate of green) was useful as a means of observing leaf expansion as well as damage by late spring frosts. However, the results of the camera test using model leaves suggested that this index was not sufficiently sensitive to detect subtle decreases in the chlorophyll concentration. Amongst colour indices, Hue was the most robust metric for different cameras, different atmospheric conditions and different distances. The test also revealed that Hue might be useful for tracking the nitrogen status of leaves.
- Modelling results using a light use efficiency model for GPP showed a strong relationship between GPP and Hue, which was stronger than the relationships based on alternative traditional indices.

Several recommendations are outlined below to support the current results and improve the use of camera systems to observe forests under future climate change.

- Greater replication in different years and at different sites is essential to establish the observation method using the camera system; this requires co-ordination and mounting of camera systems at tower sites in international networks such as ICOS (the Integrated Carbon Observation System).
- Of all the candidate colour indices, Hue is the most promising for tracking the status of the forest canopies, as it was least affected by camera settings and by atmospheric conditions, and it had a good relationship with GPP (**Paper I, II, and III**). We propose the use of Hue as a colour index for tracking phenology and as a predictor of productivity by researchers analysing images of various types of vegetation.
- The camera test using leaf models suggested a good relationship between Hue and inferred chlorophyll concentration (**Paper III**). To clarify the meanings of colour change, it is crucial to carry out comprehensive studies using different camera systems, spectroscopy and pigment analysis. This should lead to the

development of a model to estimate the colour components of images for leaves under different nutrient status.

- The colour settings influenced the image colour, particularly for the surveillance camera systems (**Paper II, and III**). Although some camera networks have proposed their standard protocols, this does not seem to represent the best solution. It is suggested to develop a standard protocol identifying camera types, camera settings and also colour analysis to detect phenological events. Development of a European protocol will soon follow, based on this work and pilot studies at other European sites (Figure 1.3).

- Digital images at Alice Holt have demonstrated the occurrence of biotic (oak mildew) and abiotic (late frost) stresses as well as the timing of phenological events at high frequency (**Paper II**). Long-term observations using relatively low-cost camera systems will contribute to a better understanding of forest response to climate change and aid developing mitigation and adaptation strategies. Expanding camera networks in forests world-wide is strongly recommended.

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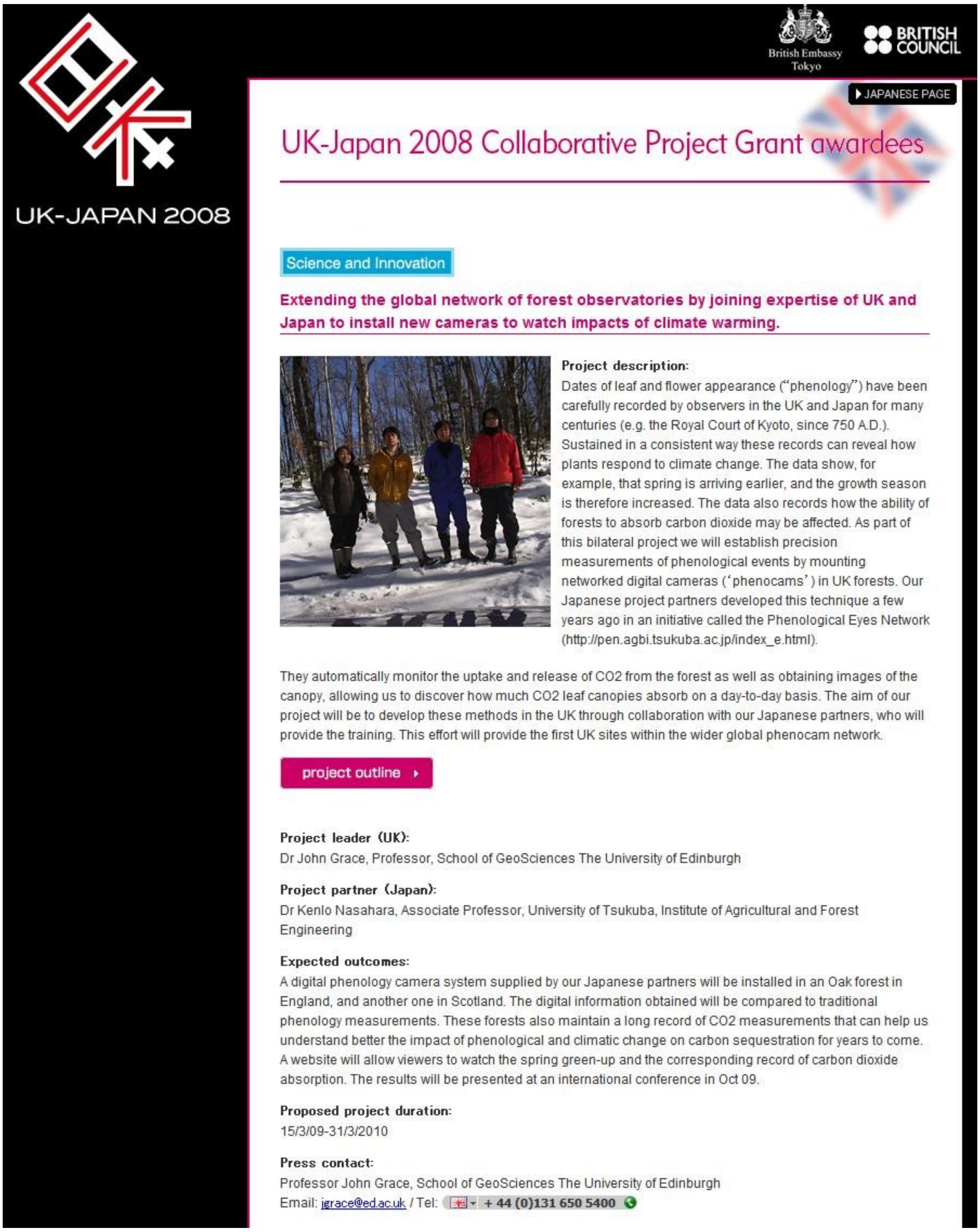
Appendix

A.1 UK-Japan 2008 Collaborative Project Grant

In early 2009 we applied for a 'UK-Japan 2008 Collaborative Project Grant Award' offered by the British Embassy Tokyo and British Council, which commemorated the 150th anniversary of official diplomatic relations between Japan and the UK showcasing the UK's contemporary creativity in science and innovation. With the help from, Professor John Grace, Professor Maurizio Mencuccini, Dr. Lisa Wingate and Dr. Caroline Nichol, funding for the project to install a camera system developed by Phenology Eyes Network in Japan at a tower in the UK Alice Holt Fluxsite was awarded. Under the project leader, Professor John Grace, I managed the activities of scientific exchange between researchers in UK and Japan including communicating with the project partner in Japan, managing budget and expenses, and reporting to the Embassy. The attached below are the announcement of the award and the final report.



British Embassy Tokyo

BRITISH COUNCIL

UK-JAPAN 2008

JAPANESE PAGE

UK-Japan 2008 Collaborative Project Grant awardees

Science and Innovation

Extending the global network of forest observatories by joining expertise of UK and Japan to install new cameras to watch impacts of climate warming.

Project description:
Dates of leaf and flower appearance ("phenology") have been carefully recorded by observers in the UK and Japan for many centuries (e.g. the Royal Court of Kyoto, since 750 A.D.). Sustained in a consistent way these records can reveal how plants respond to climate change. The data show, for example, that spring is arriving earlier, and the growth season is therefore increased. The data also records how the ability of forests to absorb carbon dioxide may be affected. As part of this bilateral project we will establish precision measurements of phenological events by mounting networked digital cameras ('phenocams') in UK forests. Our Japanese project partners developed this technique a few years ago in an initiative called the Phenological Eyes Network (http://pen.agbi.tsukuba.ac.jp/index_e.html).

They automatically monitor the uptake and release of CO2 from the forest as well as obtaining images of the canopy, allowing us to discover how much CO2 leaf canopies absorb on a day-to-day basis. The aim of our project will be to develop these methods in the UK through collaboration with our Japanese partners, who will provide the training. This effort will provide the first UK sites within the wider global phenocam network.

project outline

Project leader (UK):
Dr John Grace, Professor, School of GeoSciences The University of Edinburgh

Project partner (Japan):
Dr Kenlo Nasahara, Associate Professor, University of Tsukuba, Institute of Agricultural and Forest Engineering

Expected outcomes:
A digital phenology camera system supplied by our Japanese partners will be installed in an Oak forest in England, and another one in Scotland. The digital information obtained will be compared to traditional phenology measurements. These forests also maintain a long record of CO2 measurements that can help us understand better the impact of phenological and climatic change on carbon sequestration for years to come. A website will allow viewers to watch the spring green-up and the corresponding record of carbon dioxide absorption. The results will be presented at an international conference in Oct 09.

Proposed project duration:
15/3/09-31/3/2010

Press contact:
Professor John Grace, School of GeoSciences The University of Edinburgh
Email: jgrace@ed.ac.uk / Tel: + 44 (0)131 650 5400

Figure A.1 Announcement of UK-Japan 2008 Collaborative Project Awardees.

UK-JAPAN 2008 COLLABORATIVE PROJECT GRANT

Science and Innovation

Installing a Phenological Camera

Final Report

Project leader (UK): **Dr John Grace, Professor**
School of GeoSciences, The University of Edinburgh, Edinburgh, United Kingdom

Project partner (Japan): **Dr Kenlo Nasahara, Associate Professor**
Institute of Agricultural and Forest Engineering, University of Tsukuba, Tsukuba, Japan

1. Introduction

Surprisingly little is known about how the timing of spring leaf onset (known as 'bud-break') and autumn leaf senescence affect the balance between photosynthesis and respiration of forest ecosystems. This balance is crucial to understand how the biosphere is responding to, and is helping to ameliorate, the effects of global change. Eddy covariance sites are experimental sites, which aim to monitor surface-atmosphere exchanges of CO_2, water and energy. The worldwide network of eddy covariance sites (FLUXNET) is monitoring the fluxes associated with the regional networks such as CarboEurope-IP, AmeriFlux and AsiaFlux. Phenology Eyes Network or PEN is the network of long-term ground observatories mostly located in AsiaFlux sites in Japan (http://www.pheno-eye.org/index_e.html, started in 2003). It aims for the continuous monitoring of terrestrial ecosystem for satellite validation using optical instruments on ground.

Mounting networked digital cameras is a simple method to observe the timing of canopy growth and senescence. The latest studies in webcam-based phenological monitoring (e.g. Richardson et al. 2007) indicated that webcams offer an inexpensive means to quantify the phenological changes. Although a recent FLUXNET survey has uncovered at least 26 cameras already 'keeping on eye' on canopies including the continent Europe (Wingate et al. 2008), no camera had been installed in such sites in UK prior to 2009. With the collaboration between the University of Tsukuba, the University of Edinburgh and the Forest Research, the installation of a digital camera system has now been carried out to monitor the deciduous broadleaf forest in Alice Holt, Surrey. This became the first canopy observation by a digital camera in a flux site in UK.

2. Activities

With the Japanese partner's help, a phenological camera was successfully installed in spring 2009 and the seasonal change of forests has been monitored for over a year. The project members in UK visited to Japan in autumn 2009 and Japanese partner visited to UK in 2010 to share the knowledge and methodology in the research field and present the current results.

2.1 Camera installation and monitoring

The automatic digital fish-eye camera system (ADFC) is the system to observe phenology and sky-condition developed by the Phenology Eyes Network (PEN). An ADFC system was loaned by the Japanese partner and installed on 24th February 2009 on a CO_2 flux

- 1 -

measurement tower in Alice Holt, Surrey (51° 10' N, 0° 51' W) with the assistance of staff in the Forest Research Alice Holt Research Station (Fig. 1a). At first, the system was unstable after the installation because of unforeseen technical difficulties. However, thanks for Japanese partner's advice the problem was resolved by the middle of March and the camera system became stable. The camera has captured the seasonal change of the deciduous forest dominated by pedunculate oak *Quercus robur* and some ash *Fraxinus excelsior* (Fig. 2b). The images have been uploaded on the website of our Japanese partner, Phenological Eyes Network (PEN, http://pen.agbi.tsukuba.ac.jp) to open the public.

In spring, the appearance of new oak leaves was observed on the taken images on a daily basis followed by the budbreak of ash trees. Mildew disease on the oak trees was seen in summer and the progress of autumn colouring was monitored. Digital cameras store images using digital numbers in three colour signals, red, green and blue (RGB). We screened the images captured between 12 noon and 2pm to minimise the influence of the sunlight and analysed the strength of each colour. In 2009 the green signal dramatically increased in the spring onset season, while the red signal increased in the autumn colouring season (Fig. 2c). In spring 2010, the decline due to the damage of the late frost was seen. The results proved that the observation using a phenological camera is useful for the quantitative analysis as well as the qualitative monitoring.

In the spring 2009, Forest Research also installed a CCTV-type camera system on the same tower. Together with the research group in Forest Research, we did the same analysis to compare the images taken by the two cameras. Although the trends of seasonal transition in colour were similar, the values of RGB signals were different. In order to investigate the sensitivity of cameras to colour signals, we are going to conduct camera experiments using colour charts purchased with the remaining amount.

Meanwhile, we installed a similar system at Griffin, Aberfeldy Scotland, another CarboEurope IP flux site, managed by the University of Edinburgh (56° 36' N, 3° 47' W). This one is a coniferous forest. Two digital cameras failed during the test. We developed an alternative camera system which became operational on the 24m tower in the Sitka spruce plantation forest on 7th May 2009 (Fig. 2a). The camera clearly captured the budbreak of new shoots in the summer (Fig. 2b). This also detected by the increase of green signal (Fig. 2c). Unfortunately, a problem of power generator occurred in October has suspended the camera work. Electricity will soon be installed in the site, which will provide stable power supply. We hope the camera system re-start shortly.

- 2 -

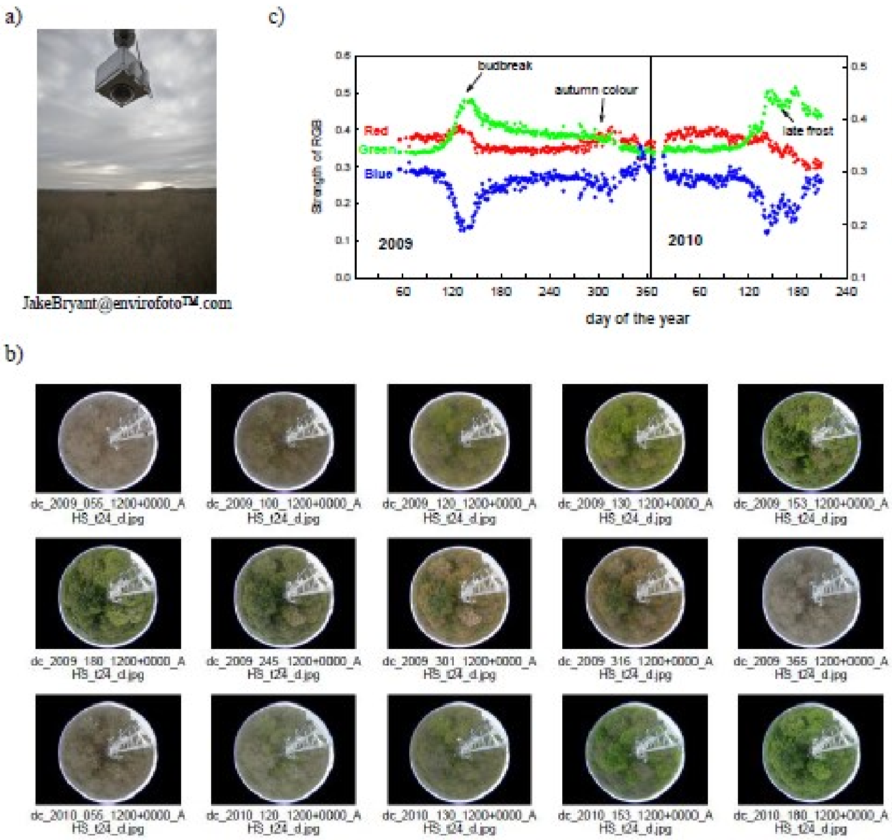


Fig. 1 The camera installed in Alice Holt, Surrey (a), the canopy phenology observed on images (b), and the results for the strength of extracted colour signals (red, green and blue) from the digital images (c). In 2010, the budbreak started later than the previous year and the effects of late frost were observed.

Fig. 2 The camera installed in Griffin, Perthshire (a), the canopy image of Sitka spruce (b) and the strength of colour signals (c). Unfortunately, the observation has stopped due to power failure since October 2009.

- 3 -

2.2 Visit of British Partner to Japan (October 2009)

In October 2009, three project members in Britain went to Japan to attend an international conference in Sapporo and visit three observation sites.

FLUXNET is a global network of micrometeorological tower sites that use eddy covariance methods to measure the exchanges of carbon dioxide and the AsiaFlux network covers the South East Asia region. In the end of October, the 8th AsiaFlux workshop was held in Sapporo, Japan (http://www.japanflux.org/asiafluxws2009/, Fig. 3a). More than 180 scientists and students from 16 countries took part in the workshop entitled 'Integrating Cross-scale Ecosystem Knowledge: Bridge and Barriers'. Dr Lisa Wingate had invited for an oral presentation and introduced our results of monitoring in Alice Holt and Griffin comparing with other sites (Fig. 3b). The PhD student, Toshie Mizunuma presented a poster about the colour analysis using a year-through images of a Japanese beech tree in Mt Tsukuba provided by the Japanese partner. Professor John Grace and Dr Kenlo Nasahara were also invited for the workshop as the key note speakers. This provided a great opportunity for the project members in both UK and Japan to meet face to face and discuss the further activities.

Wingate and Mizunuma also had two day fieldtrip to visit three PEN sites in Japan: Kiryu Experimental Watershed (KEW) site managed by Kyoto University, Fuji-Hokuroku (FHK) managed by National Institute for Environmental Studies (NIES) and National Institute of Advanced Industrial Science and Technology (AIST), and Fuji-Yoshida (FJY) flux sites Forestry and Forest Products Research Institute (FFPRI). The knowledge and experience about the camera systems in the three sites were discussed.

a) b) c) d)

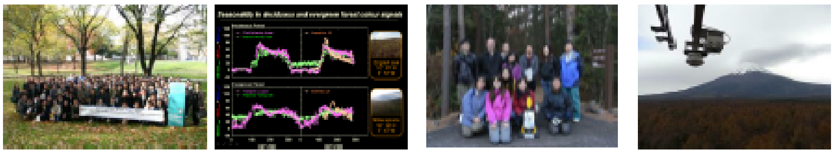


Fig. 3 The photo in the 8th AsiaFlux Workshop in Sapporo (a) and a slide presented by Dr Wingate (b). Fieldtrip to two PEN sites in Fujiyoshida (c) and camera system on an observation tower in Fuji-Hokuroku site (d).

2.3 Visit of Japanese Partner to UK (April 2010, June 2010)

On behalf of Japanese partner, Dr Shin Nagai of Japan Agency for Marine-Earth Science and Technology (JAMSTEC) who is one of core members of PEN, visited UK in April 2010 and June 2010 to attend conferences and help to install another camera system.

The Botanical Society of Scotland held International conference on Phenology: Plant ecology and diversity on 7th – 9th April in Edinburgh (http://www.botanical-society-scotland.org.uk/content/phenology-conference-2010). Prominent academics in plant phenology from Europe and Australia were invited as key-note speakers. We had an opportunity to demonstrate our collaborative project. Nagai presented the activity of PEN and the recent achievements and Mizunuma introduced our installation project with the preliminary results. This has developed a new collaboration with a research group led by Professor Annette Menzel of Technical University of Munich, Germany.

The second visit co-incided with an international conference on 14th – 17th June in Dublin organised by Trinity College Dublin (http://www.tcd.ie/Botany/phenology/2010/). From 24 countries from Europe, North America, South America, Australia and Japan, 125 attendees gathered the conference titled 'Phenology 2010 - Climate change impacts and adaptation'. Again, we presented the achievements of our collaborative project in front of the global phenological scientists. At the satellite workshop for land product validation subgroup coordinated by National Aeronautics and Space Administration (NASA), Nagai's talk about the recent results using PEN's ground observation data attracted the audience to lead the new collaboration between Europe, USA and Japan toward a new phenology product.

The two visits provided excellent opportunities for the project members of PEN, Forest Research and University of Edinburgh to discuss the future research. Nagai visited the Alice Holt Research Forest twice to help the installation of another camera system. The second fish-eye camera in Alice Holt was mounted upward on a caravan next to the flux tower (Fig.4c, d). The upward camera allows us to estimate leaf area index (LAI) which represents the vegetation growth. In addition to the colour signals from the downward camera, the index will tell us more about the phenology of forest canopy.

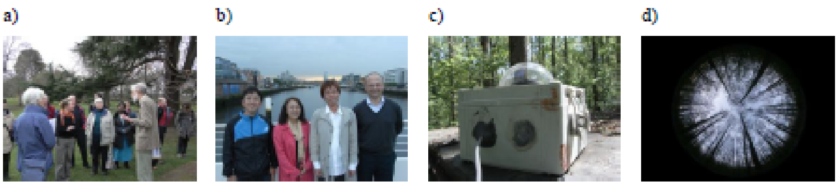


Fig. 4 The photo at the Phenology Conference in Edinburgh (a) and Phenology 2010 in Dublin (b). A new camera system installed on a roof of caravan in Alice Holt Research Forest (c) and an image taken by the camera (d).

- 5 -

3. Financial details

The following is the expenditure covered by the Grant.

Expenditure	Item	Amount
1. Fieldwork at Alice Holt, Surrey, UK		**¥ 77,957**
• Installation of a phenology camera system	Transportation	¥ 56,914
• Monitoring images	Accommodation	¥ 21,043
2. Fieldwork at Griffin, Aberfeldy, UK		**¥ 141,140**
• Installation of a phenology camera system	Transportation (*)	N/A
• Monitoring images	Repair of equipment	¥ 141,140
	(*) Covered by another budget.	
3. Visit of UK Partner to Japan (October 2009)		**¥ 399,172**
• Asiaflux workshop at Sapporo	Transportation	¥ 276,489
• Project meeting	Accommodation	¥ 102,530
• Field tour to PEN sites	Conference	¥ 20,153
4. Visit of Japanese Partner to UK (April 2010)		**¥ 343,401**
• Phenology conference at Edinburgh	Transportation	¥ 151,302
• Project meeting	Accommodation	¥ 85,237
• Installation of a camera system in Alice Holt	Conference	¥ 69,432
	Communication	¥ 1,841
	Install equipment	¥ 35,589
5. Visit of Japanese Partner to UK (June 2010)		**¥ 485,402**
• Phenology 2010 in Trinity College Dublin	Transportation	¥ 277,977
• Project meeting	Accommodation	¥ 132,104
• Maintenance of camera system in Alice Holt	Conference	¥ 75,322
6. Misc		**¥ 54,067**
• Testing colour sensitivity of cameras	Test equipment	¥ 54,067
Total cost of the project		**¥ 1,501,139**

4. Presentations

The following is the list of presentations under the auspices of the UK-Japan collaborative project award.

Wingate, L., Richardson, A. D., Nasahara, K. N., Braswell, B., Jacobs, N, Mizunuma, T., Clement, R., Wilkinson, M., Morison, J., Grace, J. and FLUXNET webcam network (2009) Keeping an eye on the carbon balance linking canopy development and Net Ecosystem Exchange using an international webcam network. AsiaFlux 7th Workshop,

- 6 -

10/2009, Sapporo. (oral)

Mizunuma, T., Koyanagi, T., Nasahara, K.N., Mencuccini, M., and Grace, J. (2009) The optimal colour index for the photographic recording of leaf phenology. AsiaFlux 7th Workshop, 10/2009, Sapporo. (poster)

Nagai, S. (2010) Comprehensive ground observation network connecting satellite remote-sensing with in situ ecosystem observations: Phenological Eyes Network (PEN). International Conference on Phenology: Plant ecology and diversity. Edinburgh, 04/2010. (oral)

Mizunuma, T., Wilkinson, M., Mencuccini, M., Grace, J., Morison, J. L. (2009) The use of digital cameras for remote assessments of forest phenolgy; a modern approach to an old problem. International Conference on Phenology: Plant ecology and diversity. Edinburgh, 04/2010. (oral)

Nagai, S. (2010) Ecological examination of the phenology detection technique by using continuous digital camera images in a deciduous broad-leaved forest, Japan. Phenology 2010 - Climate change impacts and adaptation, 06/2010, Dublin. (poster)

Mizunuma, T., Koyanagi, T., Nasahara, K.N., Mencuccini, M., and Grace, J. (2010) The optimal colour index for the photographic recording of leaf phenology. Phenology 2010 - Climate change impacts and adaptation, 06/2010, Dublin. (poster)

Nagai, S (2010) Phenological Eyes Network (PEN). An International Workshop on the Validation of Satellite-based Land Surface Phenology Products. Dublin, 06/2010. (oral)

John Grace, Edinburgh, 19.8.10

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A.2 Tree Phenology in Forest Monitoring

A colleague at Forest Research (Alice Holt, UK), Dr. Matthew Wilkinson, kindly invited me to co-author a chapter about tree phenology in a book titled '*Forest Monitoring: Methods for terrestrial investigations in Europe with an overview of North America and Asia*'. A picture of the book cover and the related pages were extracted below.

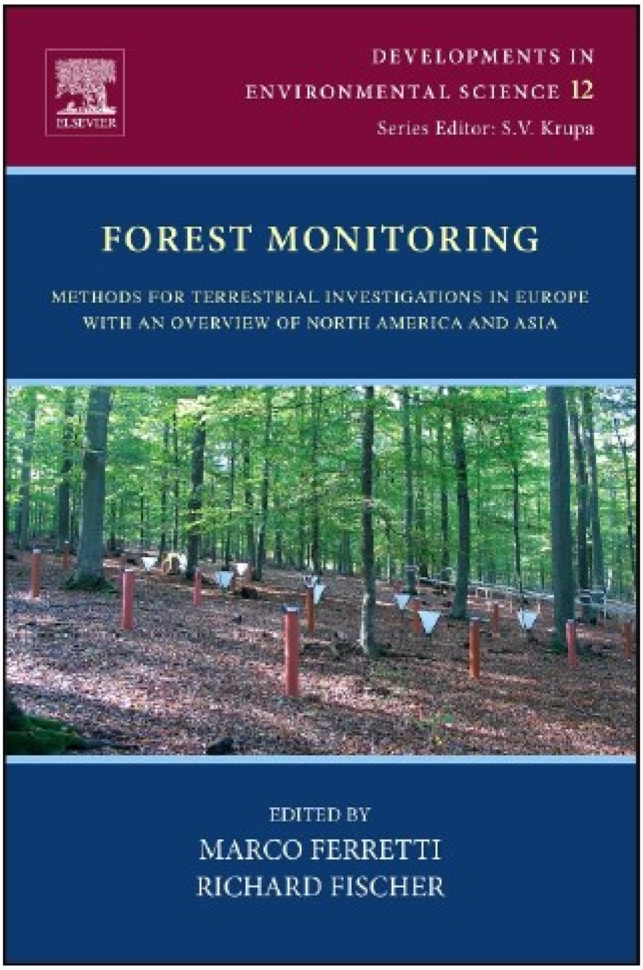

Figure A.2 Cover of Forest Monitoring.

Chapter 9

Tree Phenology

Urša Vilhar*[,1], Egbert Beuker[†], Toshie Mizunuma[‡], Mitja Skudnik*, François Lebourgeois[§], Kamel Soudani[¶] and Matthew Wilkinson[||]
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[†]Finnish Forest Research Institute Metla, Punkaharju, Finland
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[§]Laboratoire d'Etude des Ressources Forêt Bois (LERFoB), AgroParisTech, ENGREF, UMR1092, Nancy, France
[¶]Laboratoire Ecologie, Systématique et Evolution, CNRS, University of Paris Sud 11, Orsay, France
[||]Forest Research, Alice Holt Lodge, Farnham, Surrey, United Kingdom
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Chapter Outline

9.1 INTRODUCTION

Phenology has been defined as the study of cyclical biological events. In plants, this can include flowering, leaf unfolding (or budburst), seed set and dispersal, and leaf fall in relation to climatic conditions (Davi et al., 2011). Plant phenology has been proposed as an indicator of climatic difference

Developments in Environmental Science, Vol. 12. http://dx.doi.org/10.1016/B978-0-08-098222-9.00009-1

Phenological observations at the plot level can be carried out by technical staff. They are not cost intensive as they may be conducted in parallel with the collection of samples taken at the plots in regular time intervals. A frequency of at least once every two weeks during the growing period is recommended.

Phenological observations at the individual tree level are carried out at least once a week during the critical phases, but daily observations are the optimum.

9.5.2 Observations Using Indirect Techniques

9.5.2.1 Terrestrial Digital Image Photography

As the relative costs of digital cameras have decreased and image quality has increased, the use of digital cameras for forest phenology monitoring has been adopted rapidly. The advantages of remote digital camera systems over traditional manual observations are numerous: first, there is a reduced need for an observer to make regular site visits, which can often be costly and time consuming, especially in remote forest areas. Second, the high frequency with which camera-based systems can capture canopy images, for example, daily or even hourly makes the accurate observation of key phenological events more likely. Third, by using the digital values of red, green, and blue taken from the image file, the time course of vegetation indices can be quantitatively analyzed (Richardson et al., 2007).

Several different types of digital camera systems have been used across a range of sites to record high frequency phenological images. A test using 11 different cameras at a deciduous forest in North America showed that the choice of camera and image format did not make large differences in phenological recording (Sonnentag et al., 2012). Digital camera systems can be used to provide a permanent photographic record suitable for manual inspection. These photos can be compared with images or descriptions of standard phenological stages (Table 9.1), an approach which potentially removes the biases associated with field-based assessments reliant on multiple observers. Using color strength, optical vegetation indices can be determined (e.g., Richardson et al., 2007). The time courses of these vegetation indices are useful in detecting key phenological events, and where photos from several years are available, these can be used to quantify the interannual variation (Figures 9.2 and 9.3). In this example, differences in the timing of the green-up pattern over 3 years at an oak forest in the south east of England are evident, with the earliest spring occurring in 2011; damage to the canopy caused by a late air frost in 2010 can also be seen. Despite variations that may occur due to changes in light conditions, camera-based techniques can provide useful information about the timing of key phenological events such as budbursts or leaf fall.

9.5.2.2 Applying the Normalized Difference Vegetation Index

For many years, spectral vegetation indices (SVI) that combine visible and near infrared light reflected by vegetation, such as the normalized difference

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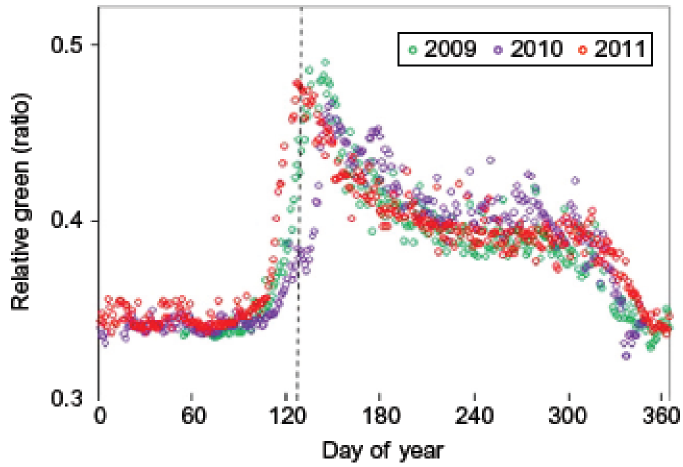


FIGURE 9.2 Relative proportion of green in digital images of an oak forest canopy taken at the Alice Holt Research Forest in the South of England. The dotted line shows the difference in canopy state on day 124 (4th of May) in each year.

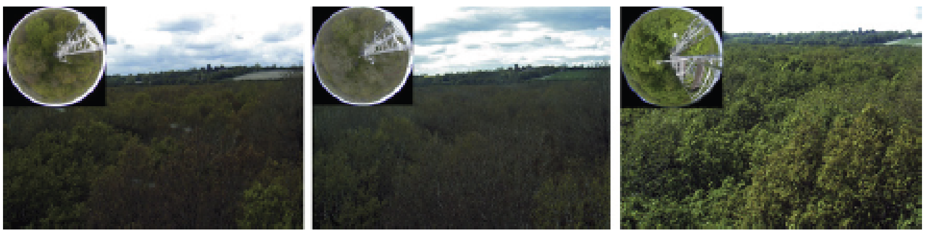


FIGURE 9.3 Photographs of an oak forest canopy at the Alice Holt Research Forest in the South of England, the images were taken on day 124 (4th of May) in 2009, 2010, and 2011. The main photos were taken using a NetCam SC 5 MP, inset photos were taken using an automatic-capturing digital fisheye camera (ADFC) system, part of the Phenological Eyes Network (http://pen.agbi.tsukuba.ac.jp/index_e.html).

vegetation index (NDVI), have been used to quantify the phenology of different ecosystems from ground- (Soudani et al., 2012) and satellite-based measurements (Soudani et al., 2008). NDVI is determined from red and near infrared radiances measured above the canopy and is commonly used in remote sensing studies because it is sufficiently sensitive to capture small changes in the amount of vegetation greenness. In the framework of the French network of long-term measurements of carbon, water, and nutrients fluxes, many forest sites have been equipped with laboratory-made NDVI sensors to monitor the temporal dynamics of canopy structure and phenology with daily resolution (Soudani et al., 2012). This approach has been applied to other herbaceous and forest ecosystems across the world. Results show that NDVI time series provide effective estimates of photosynthetic biomass and constitute accurate estimates of dates of main phenological events such as

A.3 Media Coverage

The study of **Paper II** has received media attention and the topic was covered by the three media.

A.3.1 Press release by British Ecological Society

Paper II was accepted by Functional Ecology, one of journals published by British Ecological Society (BES). The editor of the journal invited us to the video highlight and the press release to introduce the article. The 3-minute video was created with help by Bryan Pickering and Colin Morris of the video team of University of Edinburgh and uploaded on Functional Ecology YouTube site (http://youtu.be/tbzcMrJi61Q). Coinciding with the BES Annual Meeting in Birmingham in December 2012, BES Press Officer, Becky Allen issued news article including the link of the video which appeared on Science Daily website (http://www.sciencedaily.com/releases/2012/12/121219223231.htm). The news article titled '*Pics, Shoots and Leaves: Ecologists Turn Digital Cameras Into Climate Change Tools*' is shown below.

ScienceDaily
Your source for the latest research news

Web address:
http://www.sciencedaily.com/releases/2012/12/121219223231.htm

Pics, Shoots and Leaves: Ecologists Turn Digital Cameras Into Climate Change Tools

Dec. 20, 2012 — As digital cameras become better and cheaper, ecologists are turning these ubiquitous consumer devices into scientific tools to study how forests are responding to climate change. And, they say, digital cameras could be a cost-effective way of visually monitoring the spread of tree diseases. The results -- which come from 38,000 photographs -- are presented at this week's British Ecological Society's Annual Meeting at the University of Birmingham.

Because trees fix carbon dioxide (CO_2) from the atmosphere and store carbon as biomass and soil organic matter, forests play a vital role in helping regulate climate change. Forests are also affected by climate change, with buds bursting sooner as spring arrives earlier, and ecologists need to understand how this process affects the amount of carbon trees can lock away from the atmosphere.

Studying how forests take up CO_2 during photosynthesis is a complex and costly business involving a world-wide network called FLUXNET, which monitors the exchange of CO_2 between the atmosphere and forests from more than 500 instrument towers worldwide using a technique known as eddy covariance. Now, Toshie Mizunuma of the University of Edinburgh has developed a way of using the seasonal changes in forest colour captured in digital photographs to calculate how much CO_2 deciduous trees soak up.

"Reliably predicting CO2 flux isn't easy because it varies a lot due to changes in weather and alterations in forest metabolism caused by pests and diseases. We also still do not understand what controls the timing of leaves coming out in spring and falling in autumn. So we need a cheaper, simpler way of gathering this long-term data," Mizunuma explains.

To work out how to use digital cameras to capture this data, in 2009 the team working with Mizunuma set up two different camera systems in Alice Holt Forest, Hampshire. A commercial oak forest planted in the 1930s, Alice Holt contains a 90 ha research plot which is part of several long-term studies including the UK Environmental Change Network (ECN) and the European forest health network ICP Forests.

To work out how to use digital cameras to capture this data, in 2009 the team working with Mizunuma set up two different camera systems in Alice Holt Forest, Hampshire. A commercial oak forest planted in the 1930s, Alice Holt contains a 90 ha research plot which is part of several long-term studies including the UK Environmental Change Network (ECN) and the European forest health network ICP Forests.

The two cameras were set at different angles: an outdoor webcam with a near-horizontal view and a commercial 'fish-eye' digital camera looking down at the canopy from the top of a tower. The cameras snapped photos every 30 minutes during daylight for two years -- a total of 38,000 pictures, of which the four around midday were analysed.

She then analysed the colour of the forest canopy and compared it to FLUXNET measurements at the site: "The transition of colours from both cameras showed the seasonality of the forest: when budbreak started, the green sharply increased, gradually decreased in summer, and returned to the original level when leaves were shed; the rise of red colour was shown when oak leaves turned yellow in autumn. And the timing of the sharp increase in green coincided with the onset of carbon absorption."

"We estimated the carbon uptake using three fairly simple models, each using information about the level of incoming radiation, which is essential for photosynthesis. The modelled carbon uptake using 'hue', a parameter extracted from the photos, showed the strongest agreement with measured carbon uptake."

According to Mizunuma, the data confirm that digital cameras could be very useful in monitoring climate change effects in forests: "Our results suggest that digital cameras can be an important aid in monitoring forests and the colour signals can be a useful proxy for photosynthesis. Not only forests, one could install this system or one like it at any long term monitoring site. Long-term ecological observation is now crucial for study in climate change and biodiversity. Digital cameras provide long-run evident footage with relatively low cost without labour."

Toshie Mizunuma will present her full findings at 12:45 on Thursday 20 December 2012 to the British Ecological Society's Annual Meeting at the University of Birmingham.

A three-minute video on the research is available at: http://youtu.be/tbzcMrJi61Q

Story Source:

The above story is reprinted from materials provided by British Ecological Society (BES), via AlphaGalileo.

Journal Reference:

Toshie Mizunuma et al. The relationship between carbon dioxide uptake and canopy colour from two camera systems in a deciduous forest in southern England. Functional Ecology, December 2012; DOI: 10.1111/1365-2435.12026

A.3.2 Environment news on The New York Times Green Blog

After the news release about **Paper II** by British Ecological Society, a science writer Josie Garthwaite for The New York Times – Green Blog showed interest and featured our study into an article titled '*Capturing Climate Change Digitally*' (http://green.blogs.nytimes.com/2012/12/27/capturing-climate-change-digitally/).

The New York Times
Green
A Blog About Energy and the Environment

DECEMBER 27, 2012, 10:03 AM

Capturing Climate Change Digitally

By JOSIE GARTHWAITE

The changing palette of colors in a forest signals more than the arrival of a new season. For those who know how to look, the colors also reveal how much carbon dioxide the trees are absorbing from the atmosphere during photosynthesis, a new study suggests. By analyzing thousands of photographs of a forest canopy less than 40 miles outside London, the researchers were able to estimate carbon uptake over a two-year period based on the leaves' hues.

Forests play a vital role in mitigating the effects of climate change by taking up carbon dioxide and storing it in leaves, stems and roots. In the United States, forests absorb and store some 750 million metric tons of carbon dioxide annually, or about 10 percent of the country's carbon dioxide emissions, the Forest Service says.

But as climate change shifts the timing of seasons, buds are bursting sooner, and ecologists are working to understand how this affects forests' ability to absorb carbon dioxide.

"Reliably predicting CO2 flux isn't easy," the study's lead author, Toshie Mizunuma, a doctoral researcher at the University of Edinburgh's School of GeoSciences, said in a statement. "It varies a lot due to changes in weather and alterations in forest metabolism caused by pests and diseases."

To better understand the relationship between carbon uptake and canopy color, Ms. Mizunuma's team set up a pair of digital cameras in Alice Holt Forest, a former royal hunting ground that now has a 220-acre research plot within a commercial oak forest. The researchers, whose work appears in the latest issue of the peer-reviewed journal Functional Ecology, positioned an outdoor Webcam to view the canopy horizontally.

They set up a second camera with a fisheye lens trained downward on the canopy from atop an instrument tower. Each camera took a photo every 30 minutes during daylight for two years, capturing a total of 38,000 images, and the researchers analyzed the four photos snapped each day around midday.

Studying the timing of when trees sprout their first leaves in the springtime, flower and finally shed their leaves in the autumn, is considered one of the simplest ways to monitor how trees are responding to climate change. But the work, known as phenology, has traditionally required visits to the same tree in the same spot at least once a day, sometimes more, Ms. Mizunuma wrote in an e-mail. These manual observations are "often impractical," she said. Accessibility to the target trees may be limited, and "monitoring may be biased by observers."

More recently, remote monitoring via satellite has offered a less labor-intensive alternative, but clouds often get in the way and the area captured is so large that woodland images are often muddled with adjacent land, Ms. Mizunuma said. And in a study published this year in the Proceedings of the National Academy of Sciences (PNAS), scientists at Colorado State University and Duke University called for correction of the models now used to estimate carbon uptake based on remotely sensed greenness.

Carbon uptake by trees of nearly two dozen species dropped off weeks before leaves began to change color and to fall in the autumn, they found, suggesting that trees may sequester as much as 3 percent less carbon dioxide globally than previously thought.

This latest paper joins a growing body of research comparing direct measurements of carbon exchange in various landscapes with measures of reflected light, said Dennis Baldocchi, a professor of biometeorology at the University of California, Berkeley, who is unaffiliated with Ms. Mizunuma's team.

"Many of us are interested in providing ground truth" for the estimates of photosynthesis produced by satellites in space, he explained. In recent years, he said, researchers have increasingly used digital cameras or narrow-band spectrometers at instrument towers like the one in Alice Holt Forest. More than 500 such towers now form an international network created in the 1990s to measure carbon fluxes directly over the long term. The idea of using numbers extracted from digital images to detect a vegetation index originated in the laboratory of Andrew Richardson, a physiological ecologist at Harvard, Dr. Baldocchi said.

Ms. Mizunuma suggsted that digital cameras could combine the best of both worlds in that they provide unobstructed images that can be quantitatively analyzed at a far lower cost than previous methods. Her team extracted several parameters from the photos and mapped them against data collected at the site by the instruments on the tower. "Of all the expressions of canopy color, hue is the one that seems to have the greatest utility," the researchers write.

The rise of carbon dioxide uptake in the spring and the decline of uptake in the fall approximately dovetail with the greenness and hue of the leaves. Carbon uptake peaked when the leaves were dark green, suggesting that "hue can be a useful proxy for photosynthesis," Ms. Mizunuma said. The authors note, however, that further research is needed at other sites "to explore whether such a good relationship always exists, as it may be site- and time-specific."

It's certainly worth finding out, Dr. Balodocchi said. Exploring hue in this context "may give us another way to try and upscale carbon fluxes with cheap cameras," he said. "This is a good way to produce citizen science and study phenology well, too."

"We have years of photos at our sites with flux data, he said, "so it it s a good idea to test."

Ms. Mizunuma said that experts still do not understand what controls the timing of leaves' sprouting in the spring and falling in the autumn. What is needed, she said, is a cheap and simple way to gather data over the long term, and digital cameras could hold the key.

Indeed, as digital camera technology has improved and prices have dropped, scientists have begun to harness them for a broad range of research projects, sometimes calling on Internet users to help analyze thousands of images.

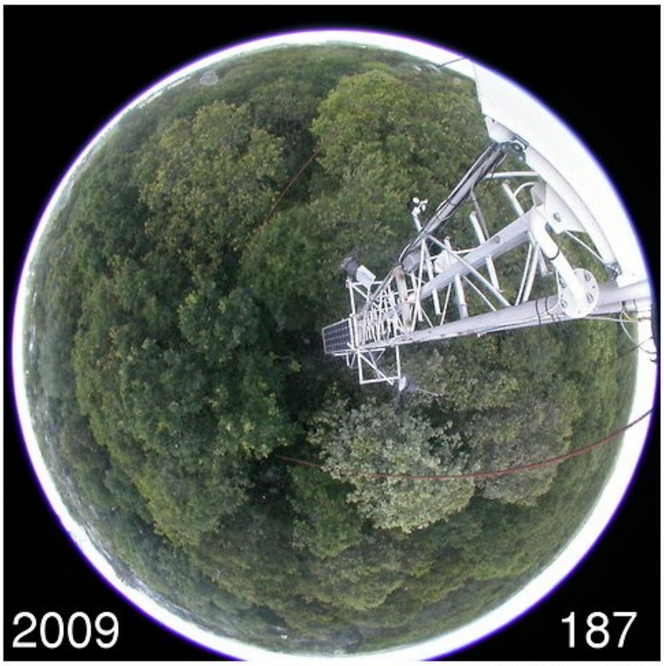
Researchers with the Zooniverse project led by the University of Oxford and Adler Planetarium, for example, have set up more than 220 camera traps throughout Serengeti National Park in Tanzania. Visitors to the Snapshot Serengeti website, launched this month, can help identify the animals.

As Chris Lintott, the Zooniverse project's director, explained to PRI's "The World," "The cameras allow us to carpet the whole place."

Meanwhile, in Greenland, the Himalayas in Nepal, Alaska and the Rocky Mountains, the Extreme Ice Survey has set up 34 cameras at 16 glaciers to track changes in the ice, seeking to give a "visual voice" to the landscape.

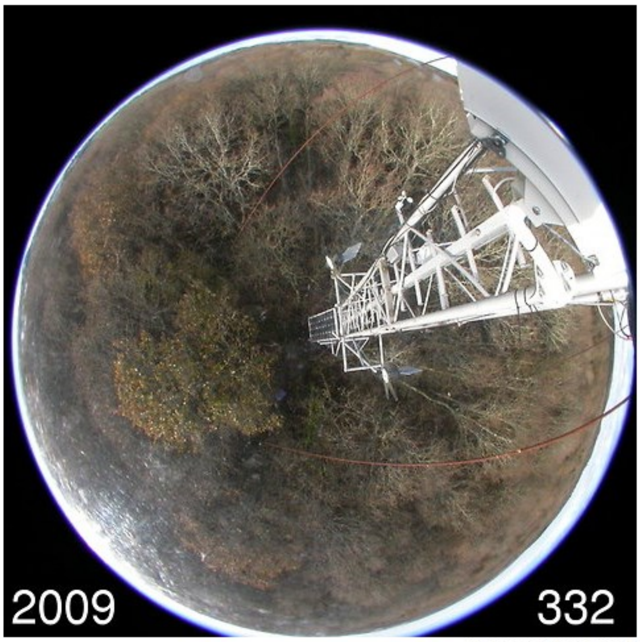
According to Ms. Mizunuma, digital cameras could also be used to visually monitor the spread of tree diseases, and similar setups could be invaluable in monitoring how vegetation responds to environmental change. "It is a well-known fact that positive response often turns into negative response at a certain point," she said, noting that leaves sprouting earlier in the year may expand the carbon-uptake period, but then increase the risk of frost damage.

As a result, she said, "long-term observation is crucial to understand how plants respond to climate change."



Phenological Eyes Network

By snapping digital images every 30 minutes during daylight hours in the Alice Holt Forest in Britain, scientists were able to measure the relationship between carbon uptake and canopy color. In this image, from July 2009, the deep green correlated with a high uptake.



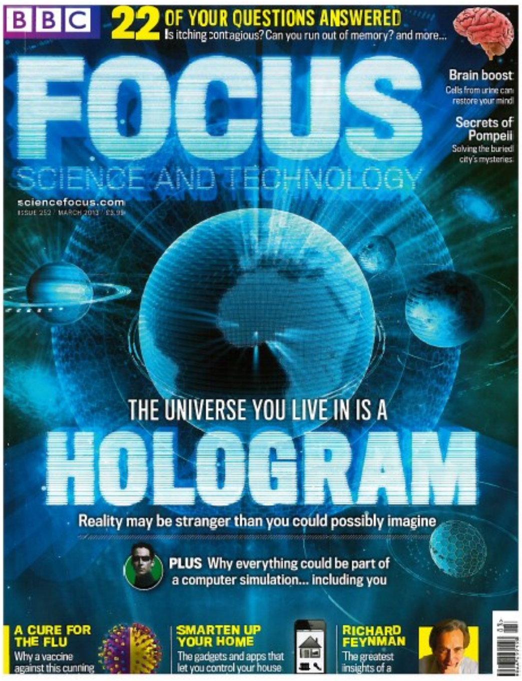
Phenological Eyes Network

The tree canopy as photographed in November 2009, when carbon uptake was lower than in the summer.

Figure A.3 Figures on NY times Green Blog.

A.3.3 News on BBC FOCUS magazine

The study using cameras seems to appeal public in terms of citizen science and a writer James Lloyds asked a telephone interview for his news article on BBC FOCUS magazine March 2013 issue. The cover of the magazine and the copy of the article titled '*Cameras capture climate-cooling efforts of trees*' are shown below.



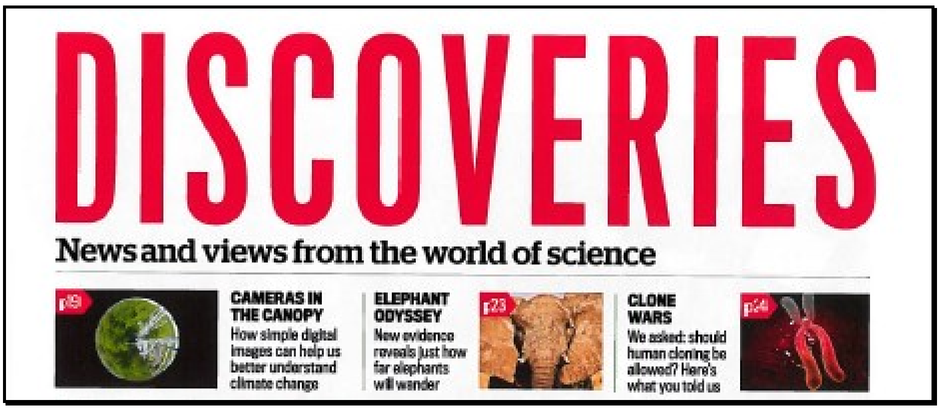
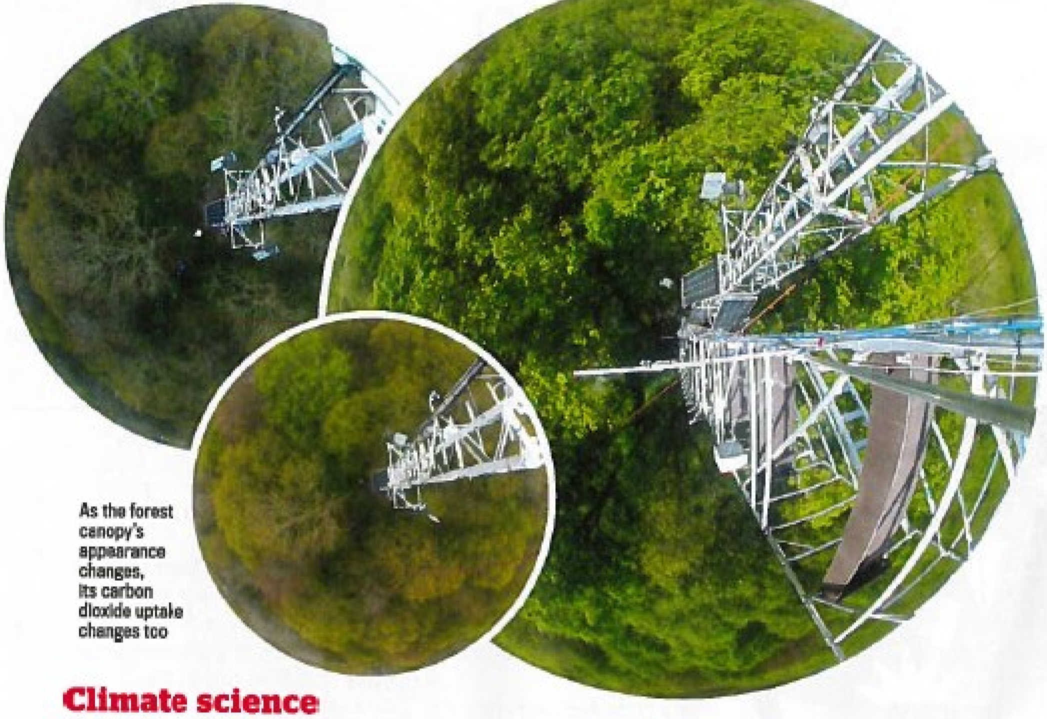


Figure A.4 Cover of BBC Focus March 2013 issue and top of 'DISCOVERIES' section.



As the forest canopy's appearance changes, its carbon dioxide uptake changes too

Climate science

Cameras capture climate-cooling efforts of trees

DIGITAL CAMERAS COULD become an important tool for monitoring the growing threat of climate change, now that ecologists have found a way of using them to measure how much carbon dioxide forests are taking up.

Forests are a vital 'sink' for the carbon released when fossil fuels are burned. A global network of tower-mounted carbon dioxide (CO_2) sensors called FLUXNET currently monitors this carbon uptake by forests. These sensors are expensive, and cover only a small fraction of the Earth's surface – but it now appears that taking a series of photos of a forest will do the same job.

University of Edinburgh ecologists fixed two cameras on Alice Holt forest in Hampshire and took a photo every half hour during daylight for two years, giving them 38,000 snaps in total. They then used image-processing software to analyse changes in the forest canopy. As expected, the strength of the green signal in the images jumped up during the spring season as the leaves came out. Of all the parameters measured, the forest canopy's colour showed the strongest agreement with measured carbon uptake.

The Edinburgh ecologists say that spring is arriving earlier each year, but it's not known how these longer growing seasons affect the amount of carbon absorbed by trees. A global network of forest-monitoring digital cameras is now being established that will provide some insights, but there's still a lot to learn.

"It's important for us to replicate the same method in other forests," says Toshie Mizunuma, a PhD student at Edinburgh. "In Alice Holt we studied an oak forest, but other trees such as maples and ash trees have different colours. So we're trying to study forests of different species."

Visit bit.ly/VWcabM to watch a video about the research.

JAMES LLOYD

A.4 Preliminary Results for Latest Images in Alice Holt

The two camera systems for the study **Paper II** captured the seasonal change of the forest canopy in Alice Holt during 2009 and 2010. Additional preliminary results using data between 2010 and 2012 are shown here. These data will be the subject of a further publication, extending the analysis made in **Paper II**.

A.4.1 Data analysis for 2010-2012

The method for processing the preliminary results followed those for **Paper II**. Since the white balance was set to 'auto', the data in 2009 were excluded. Focusing on light conditions, images taken at 12:00 were used for micro-climate data, carbon flux data and digital images. The fraction of diffuse radiation was calculated from the theoretical radiation at the top of atmosphere and the measured radiation using an empirical model (Erbs, Klein & Duffie 1982). Sky conditions were separated as 'sunny' when the diffuse fraction was greater than 0.7 and 'overcast' otherwise. Due to the delay in receiving solar irradiance data for below and above canopy, images from the upward camera were used to estimate Plant Area Index (PAI) by a custom-made Matlab code (Ryan *et al.* 2012). The sample photographs and the region of interests for RGB analysis are shown in Figure A.5.

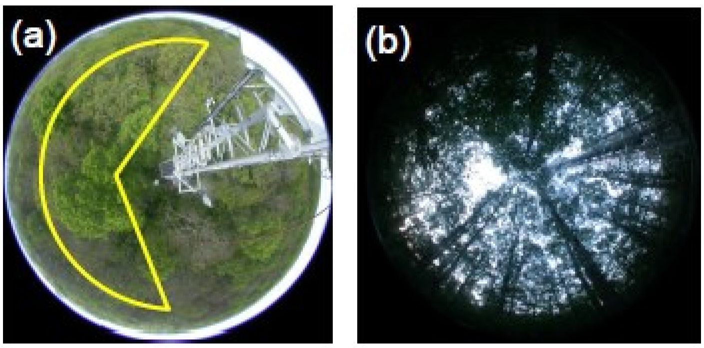


Figure A.5 Sample images and the analysed region of interest: (a) downward image (b) upward image.

A.4.2 Preliminary results

The climate conditions and carbon flux measurements are shown in Table A.1. In 2010, low minimum temperatures in the carbon uptake period caused damage because of late frost (Paper II). Such a cold spell was not seen in spring 2011 and 2012 (Figure A.6a). The annual GPP increased from 2010 to 2012, though in 2012 the global solar radiation was the lowest and the carbon uptake period was the shortest of the three study years. The annual GPPs were 11-27% lower to compare with the 12-year average annual value of 2034 gC m^{-2} y^{-1} (Wilkinson *et al.* 2012).

Table A.1 Summary of the climate conditions and the CO_2 flux measurements in the three study years at the Straits Inclosure, Alice Holt Forest, south east England.

	Whole year			Carbon uptake period		
	2010	2011	2012	2010	2011	2012
Climate conditions						
Precipitation (mm y^{-1})	747	623	1120	358	364	574
Average temperature (ºC)	9.2	10.9	9.8	14	13.9	13.2
Maximum temperature (ºC)	27.7	27.3	28.4	27.7	27.3	28.4
Minimum temperature (ºC)	-9.6	-4.6	-10.7	-3.9	0.4	-1.2
Global solar radiation (MJ m^{-2} y^{-1})	3856	4043	3878	2761	3176	2677
Carbon flux						
Carbon uptake period (day)				190	203	187
Carbon uptake start (day of year)				118	106	124
Carbon uptake end (day of year)				307	308	310
GPP (gC m^{-2} y^{-1})	1506	1678	1805	1396	1589	1697
NEE (gC m^{-2} y^{-1})	-296	-422	-398	-532	-670	-682
RUE (gC MJ^{-1})	0.83	0.88	0.99	1.08	1.06	1.35

Although the GPP values at 12:00 under the sunny conditions tended to be lower than those under the cloudy conditions, the boundary was not clear in comparison with solar radiation (Figure A.6bc). No distinctive differences were seen for S_{green} and Hue comparing the sunny and cloudy conditions (Figure A.6de).

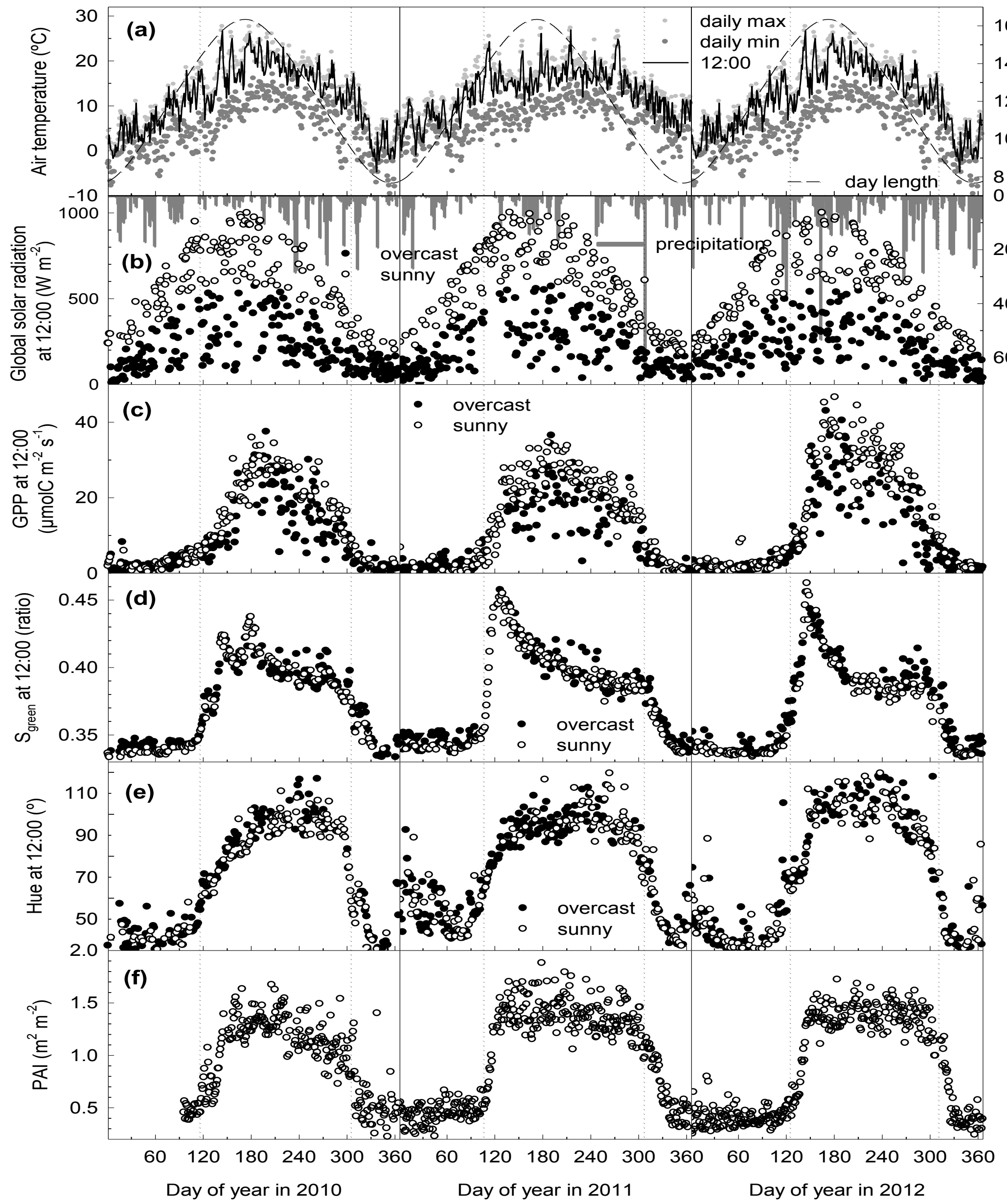


Figure A.6 Seasonal variations in: (a) air temperature and day length, (b) precipitation and global solar radiation observed at 12:00, (c) GPP measured at 12:00, (d) S_{green}, (e) Hue derived from images taken at 12:00 and (f) PAI estimated from upward images. The radiation, GPP, S_{green} and Hue were separated by the sky conditions at 12:00; open dots for sunny and closed dots for overcast conditions. Dotted lines indicate the start and end of carbon uptake period determined from GPP.

The correlation between daily GPP from the eddy flux measurements and the daily GPP modelled using S_{green} and Hue is shown in Figure A.7. Supporting the previous results (**Paper II**), the GPP using S_{green} showed a poor correlation particularly soon after the start of growing season, while the GPP from Hue showed the best result throughout the three years.

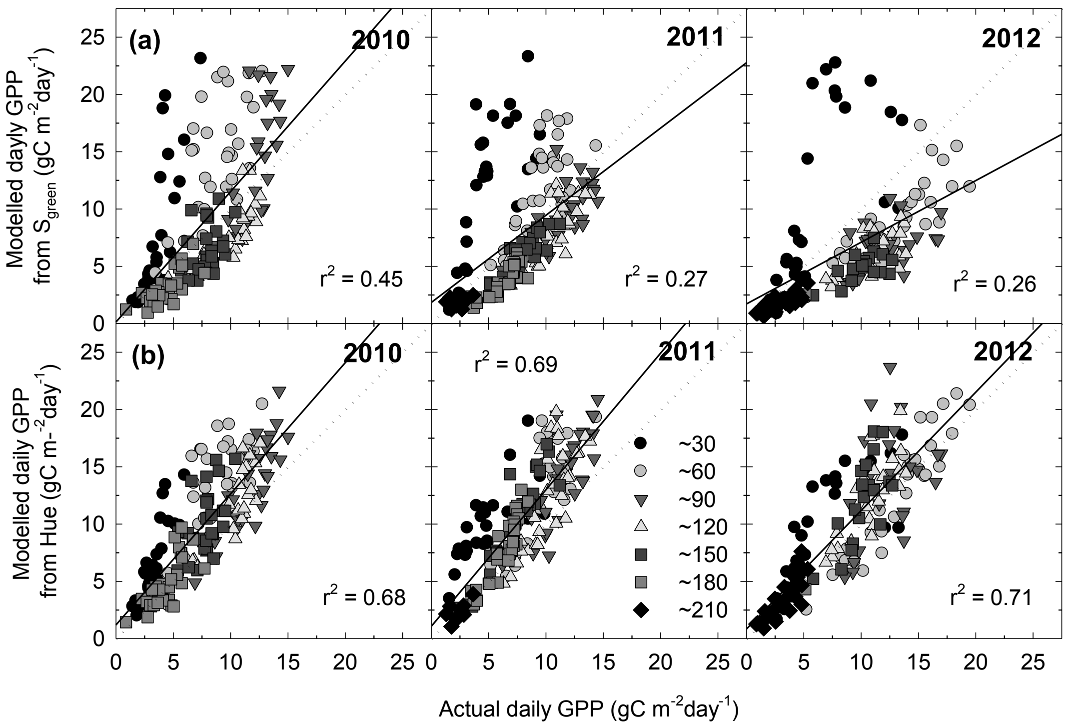


Figure A.7 Comparison of actual daily GPP during the carbon uptake period with: daily GPP estimated using (a) S_{green} and (b) Hue from images. Straight lines indicate linear regression and dotted lines indicate y = x. Symbols indicate numbers of days from the start of the carbon uptake periods.

To study the effect of sky conditions, the correlation between the GPP measured at 12:00 and the GPP at 12:00 modelled using Hue was examined (Figure A.8, Table A.2). The correlations for the overcast conditions were better than for the sunny conditions, although Hue itself was unaffected by the light conditions (cf., Fig. A.6).

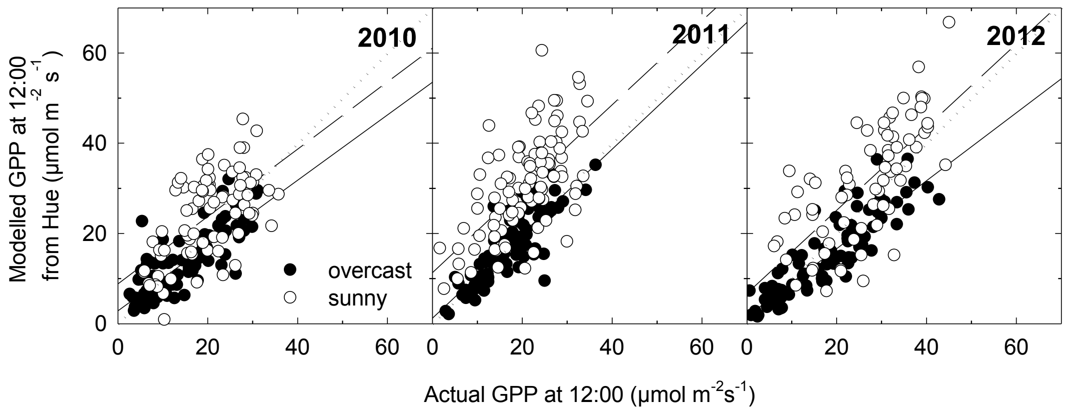


Figure A.8 Comparison of actual GPP at 12:00 during the carbon uptake period with GPP estimated using Hue from images. Open dots indicate sunny conditions and closed dots indicate overcast conditions. Dashed lines indicate linear regression for sunny conditions, straight lines indicate linear regression for overcast conditions, and dotted lines indicate y = x. The statistic results listed in Table A.2.

Table A.2 Fitting statistics of the GPP modelled using Hue. R^2 is the coefficient of determination, RMSE is the root mean square error, and n is the number of samples during the carbon uptake period.

Sky conditions	Year	r^2	Slope	RMSE (μmolC m^{-2} s^{-1})	N
All conditions	2010-2012	0.55*	0.97	8.09	501
	2010	0.54*	0.86	6.73	167
	2011	0.49*	1.1	8.37	183
	2012	0.64*	0.98	8.12	151
Sunny	2010-2012	0.42*	0.86	8.77	248
	2010	0.37*	0.75	7.54	79
	2011	0.41*	0.93	8.37	99
	2012	0.50*	0.92	9.2	70
Overcast	2010-2012	0.70*	0.78	4.51	253
	2010	0.66*	0.72	4.31	88
	2011	0.69*	0.94	4.49	84
	2012	0.78*	0.75	4.19	81

* Significant (P < 0.001).

The seasonal change of Radiation Use Efficiency (RUE) derived from measured GPP and global solar radiation showed a clear differentiation, with RUE values under overcast conditions being higher (Figure A.9). This trend agrees with previous studies (Urban *et al.* 2007; Dengel & Grace 2010). For the modelling, we estimated the efficiency based on stress factors of daily minimum temperature and vapour pressure deficit. It seems necessary to improve the estimation of efficiency for the better modelling. Direct measurements of light use efficiency using spectral reflectance and fluorescences (Zarco-Tejada *et al.* 2000a; Zarco-Tejada *et al.* 2000b; Nichol *et al.* 2002; Grace *et al.* 2007) may contribute to the better understanding of the efficiency in different sky conditions.

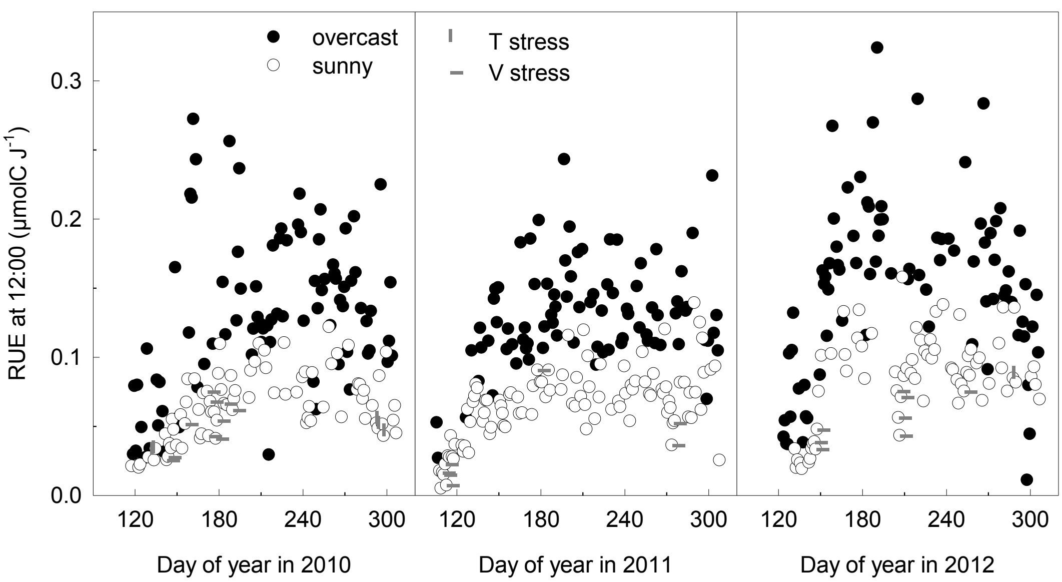


Figure A.9 Seasonal variations in actual RUE at 12:00. Open dots indicate sunny conditions and closed dots indicate overcast conditions. Vertical grey lines indicate stress caused by temperature (f(Tmin) < 0.5) and horizontal grey lines indicate stress caused by vapour pressure (f(VPD) < 0.5).

A.4.3 References

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