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Monitoring plant condition and phenology using infrared sensitive consumer grade digital cameras

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ABSTRACT

Consumer-grade digital cameras are recognized as a cost-effective method of monitoring plant health and phenology. The capacity to use these cameras to produce time series information contributes to a better understanding of relationships between environmental conditions, vegetation health, and productivity. In this study we evaluate the use of consumer grade digital cameras modified to capture infrared wavelengths for monitoring vegetation. The use of infrared imagery is very common in satellite remote sensing, while most current near sensing studies are limited to visible wavelengths only. The use of infrared-visible observations is theoretically superior over the use of just visible observation due to the strong contrast between infrared and visible reflection of vegetation, the high correlation of the three visible bands and the possibilities to use spectral indices like the Normalized Difference Vegetation Index.

This paper presents two experiments: the first study compares infrared modified and true color cameras to detect seasonal development of understory plants species in a forest; the second is aimed at evaluation of spectrometer and camera data collected during a laboratory plant stress experiment. The main goal of the experiments is to evaluate the utility of infrared modified cameras for the monitoring of plant health and phenology.

Results show that infrared converted cameras perform less than standard color cameras in a monitoring setting. Comparison of the infrared camera response to spectrometer data points at limits in dynamic range, and poor band separation as the main weaknesses of converted consumer cameras. Our results support the use of standard color cameras as simple and affordable tools for the monitoring of plant stress and phenology.

1. Introduction

Monitoring plant condition and phenology is crucial for understanding relationships between climate variability, environmental conditions, vegetation health, and productivity. Plant phenology is directly related to climate variations, both intra-annually (Polgar and Primack, 2011) and annually (Cleland et al., 2007; Linderholm, 2006; Badeck et al., 2004). Furthermore, plant phenology and condition drive primary productivity and influence other ecosystem services, such as habitat use for many species, including insects (Bale et al., 2002), birds (Papeş et al., 2012), and large herbivores (Nielsen et al., 2003, 2010; Post and Stenseth, 1999; Sharma et al., 2009). The use of consumer-grade digital cameras is recognized as a cost-effective method to obtain high temporal resolution data on vegetation processes (Richardson et al., 2009). In phenological research, studies have utilized cameras mounted on fixed locations (Bater et al., 2011a; Kurc and Benton, 2010; Nijland et al., 2012; Richardson et al., 2009) or publicly available webcam imagery (Graham et al., 2010; Ide and Oguma, 2010) to monitor vegetation changes. Because the cameras are ground-based, observations are restricted to individual plant or stand scales and are commonly referred to as 'near sensing' (Jongschaap and Booij, 2004). Despite the local scale of inquiry, these data provide a critical link to monitoring vegetation over larger areas through observational networks (Graham et al., 2010; Jacobs et al., 2009), satellite remote sensing (Hufkens et al., 2012; Zhang et al., 2003), or a combination of both (Badeck et al., 2004; Coops et al., 2012; Liang et al., 2011).

Information on vegetation development from satellite images commonly relies on indices which compare the reflectance of vegetation in multiple spectral regions. The most common indices utilize the differential response of vegetation in near infrared (*NIR*) and red (*R*) or other visible bands. The normalized difference

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vegetation index (NDVI) ($NIR-R/NIR+R$) (Tucker, 1979) is the most commonly used index (Liang et al., 2011; Soudani et al., 2012). Many studies have successfully used ground based infrared or mixed-spectrum cameras to study plant health, vegetation cover, or vegetation vigor, such as in precision agriculture (Bauer et al., 2011; Huang et al., 2010; Knoth et al., 2010), ecology (Aber et al., 2009), and archeology (Verhoeven et al., 2009), among others. The studies focus mostly on the spatial domain, while few studies analyzed time-series of *IR* or mixed imagery (Lelong, 2008). Many long term near sensing phenology studies however, rely on indices of greenness, either $2G-RB$, excess greenness, or G/RGB, green chromatic coordinate (Richardson et al., 2007; Sonnentag et al., 2012; Woebbecke et al., 1995). The difference in usage between satellite versus ground-based systems has principally been driven by atmospheric and economic considerations. Both air- and space-borne remote sensing systems are influenced by atmospheric scattering in the blue and green range and therefore better results are often obtained using longer wavelengths such as red and *NIR*. Satellite sensors are designed for Earth observation and thus include *NIR* detection capabilities, while consumer cameras are designed for taking pictures of cats and thus resemble the human vision system which has considerable overlap between especially red and green sensitivity (Konica and Minolta., 1998; Poynton, 1995). Atmospheric scattering is of little concern for near sensing as the target and the sensor are spatially much closer and shorter wavelengths like blue and green are less affected because of the reduced path length. Secondly, near sensing approaches often utilize inexpensive consumer-grade sensors (digital cameras), which facilitate autonomous remote operation and establishment of observational networks covering significant geographical areas or environmental gradients (Bater et al., 2011). In contrast, sensors that can acquire *NIR* image data are inclined to be more expensive, reducing both their flexibility in deployment and quantity of units deployed. The differences between spectral characteristics and approaches of remote and near sensing systems raise questions about the compatibility of the two approaches (Coops et al., 2012; Fisher et al., 2006). Additional research is required to improve our understanding of how these data compare both spatially and temporally, as well as how they can capture varying degrees of plant stress.

In this paper we discuss the use of single-capture infrared images for monitoring phenology and plant health. To do so we undertake two case studies, the first of which compares the performance of *IR* and true color cameras to detect seasonal development of understory plant species within a forest canopy. In contrast to the theoretical advantage of *IR* based systems, true color cameras outperform the *IR* converted sensors. Therefore, we use the second study to further explore response of *IR* and true color cameras to changes in plant health in a controlled laboratory environment. This study combines images and spectrometer data of a 52 day stress experiment on *Buxus sempervirens* plants. We use the spectrometer data to simulate the response of different camera systems to changes in plant health to help explain the performance of standard and converted consumer cameras in vegetation studies. Our main objective is evaluating the utility of consumer grade digital cameras, specifically with infrared conversions, for vegetation monitoring and phenology studies.

2. Methods

2.1. Infrared conversion of consumer-grade digital cameras

Consumer-grade digital cameras are fitted with either a CCD (charge coupled device) sensor or a CMOS (complementary metal-oxide-semiconductor) sensor. The silicon-based sensor substrate is generally sensitive to wavelengths between 350 nm and 1100 nm, including ultraviolet (UV) and *NIR* (Brooker, 2009). To obtain true-color images, most sensors have a Bayer color filter array (Bayer, 1976; Hirakawa and Wolfe, 2008), which combines a blue, a red and two green sensor cells into one true-color image pixel (Fig. 1). However, the filter materials (partly) transmit UV and *IR* radiation and therefore the cameras are fitted with a rejection filter that cancels out these wavelengths. It becomes possible to use standard CCD/CMOS sensors for *IR* imaging if the rejection filter is removed. A number of companies offer such conversions (e.g. Life Pixel Infrared Conversion Services, Mukilteo WA (www.lifepixel.com); LDP LCC, Carlstadt, NJ (www.maxmax.com)), or market purpose built digital cameras that are based on converted *RGB* sensors (Tetracam Inc, Chatsworth CA (www.tetracam.com)). The *IR* rejection filter is replaced by a filter that allows transmittance of *IR* and selected regions of the visible spectrum. The Bayer color filter array, on the other hand, is fused to the sensor substrate and cannot be removed. As a result, when using *RGB* cameras with the *IR* filter removed, the transmission profiles of the Bayer color channels remain, and depending on the filter choice each channel is sensitive to its original color and/or to *IR* radiation. Fig. 1 shows the sensitivity of a camera with the *IR* rejection filter replaced by a 590 nm long-pass filter. In this example, the *R*-channel records Red + *IR*, the *G*-channel records *IR* plus some component of the Green, and the *B*-channel records *IR* only. Other available long-pass filters include:

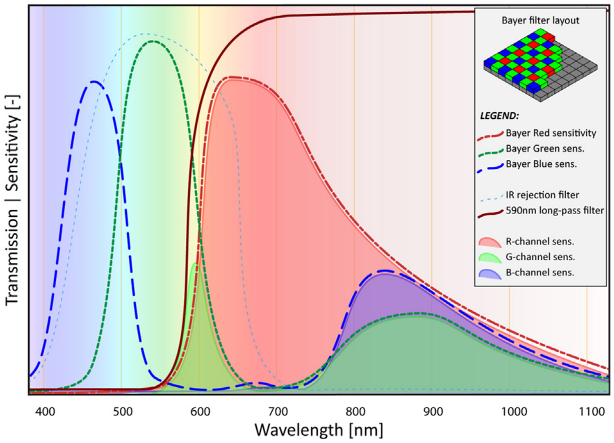

Fig. 1. Idealized filter profiles (lines) and channel sensitivity (surface) for camera with internal *IR* rejection filter replaced by a 590 nm long pass filter (after: LDP 2012, Nijland, 2012; Buil, 2012).

- Blue rejection filter (550 nm long-pass) giving R = Red + IR, G = Green + IR, B = IR-only, such as in the Tetracam ADC (Tetracam 2011 (ADC manual, v.2.3)).
- *IR* only filter (>700 nm long pass), giving *IR*-only sensitivity to all channels, but with a wider range in R (700–1100 nm) than in B and G (800–1100 nm).
- Monotone *IR* only filter (>800 nm long pass), giving a more closely balanced sensitivity between the *RGB* channels at the cost of some spectral range (800–1100 nm).

A different type of filter for vegetation research is a dual-band-pass filter that transmits light only in the 400–600 nm and 700–800 nm ranges, giving R = IR-only (700–800 nm), G = green, and B = blue (LDP LCC, 2012).

The filter choice influences the spectral sensitivity and dynamic range of the sensor. A low cutoff wavelength gives better separation between the color bands and thus allows for using these color differences in calculating band indices. However, these filters often result in a large exposure difference between R, G and B, requiring exposure compensation and causing loss of usable dynamic