REMOTE SENSING OF CROP LEAF AREA INDEX USING UNMANNED AIRBORNE VEHICLES

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ABSTRACT

Remote sensing with unmanned airborne vehicles (UAVs) has more potential for within-season crop management than conventional satellite imagery because: (1) pixels have very high resolution, (2) cloud cover would not prevent acquisition during critical periods of growth, and (3) quick delivery of information to the user is possible. We modified a digital camera to obtain blue, green and near-infrared (NIR) photographs at low cost and without post-processing. The modified color-infrared digital camera was mounted in a Vector-P UAV (IntelliTech Microsystems, Bowie, Maryland), which was flown at two elevations to obtain a pixel size of 6 cm at 210 m elevation and 3 cm at 115 m elevation. Winter wheat was planted early and late in adjoining fields on the Eastern Shore of Maryland (39° 2’ 2” N, 76° 10’ 36” W). Each planting was divided into 6 north-south strips with different nitrogen treatments, which created large variation in leaf area index (LAI). Inspection of the color-infrared photographs revealed large spatial variation in biomass and leaf area index within each treatment strip. As with most aerial photographs, there were problems in the imagery with lens vignetting and vegetation anisotropy. The green normalized difference vegetation index [GNDVI = (NIR - green)/(NIR + green)] reduced the effect of these image problems and was linearly correlated with leaf area index and biomass. With very high spatial resolution, pixels in which the soil reflectance dominates can be masked out, and only pure crop pixels could be used to estimate crop nitrogen requirements.

INTRODUCTION

Whereas aerial color and color-infrared photography has long been used to monitor crop growth (Colwell, 1956), these methods are being intensively studied for analyzing within-field spatial variability, because the imagery has high spatial resolution and can be acquired during critical periods during crop growth (Blackmer et al., 1996; GopalaPillai and Tian, 1999; Yang et al., 2000; Scharf and Lory, 2002; Flowers et al., 2003; Sripada et al., 2007). Typically, data acquired from manned aircraft are expensive compared to other types of imagery (Hunt et al., 2003). Unmanned airborne vehicles (UAVs), drones and radio-controlled model aircraft have potentially lower cost and can be flown at lower altitudes to increase spatial resolution (Fouché and Booysen, 1994; Fouché, 1999; Quilter and Anderson, 2001; Hunt et al., 2003; Herwitz et al., 2004; Hunt et al., 2005). However, low-cost and light-weight sensors are required for use with UAVs that make use of current technological advances in commercial digital cameras.

Digital photography uses silicon-diode charge-coupled detectors in cameras, where the silicon diodes have a spectral sensitivity from about 350 nm to about 1100 nm (Parr, 1996). Most digital cameras use a Bayer pattern array of filters (Bayer, 1976) to obtain red, green and blue bands for a digital image; however, the chemical basis for making these filters is proprietary. All of the Bayer filters transmit at least some NIR light through either the blue, green or red channels, so almost all commercially-available digital cameras have an internal NIR-blocking filter. On some cameras, this internal NIR-blocking filter is removable, allowing detection of reflected NIR radiation from vegetation.

Certain digital cameras (for example Kodak DCS cameras) have Bayer filters which the red, green and blue filters all transmit NIR light (Bobbe et al., 1995; Zigadlo et al., 2001). When the internal NIR-blocking filter was removed and a blue-blocking filter was placed in front of the lens, Zigadlo et al. (2001) found that the light exposing the blue channel records the NIR reflectance from vegetation. With calibration, the NIR light contributions to the green and red channels can be calculated. Therefore, with extensive post-processing, the raw digital camera image is converted into a red, green and NIR false-color image. Currently, the few color-infrared digital cameras which are commercially available are based on the method of Ziglado et al. (2001).

For many commercially-available digital cameras, only the red channel transmits measurable amounts of NIR light, so the method of Ziglado et al. (2001) cannot be applied. Furthermore, post-processing of each raw image to obtain a false-color image presents a significant extra workload that becomes a burden when processing a large number of images. Finally, the calibration of the digital camera may change with temperature and with time so the corrections for the NIR exposure in the green and red bands could change. We present a new method that allows color-infrared digital photographs to be obtained at lower cost and without post-processing. The tradeoff is that NIR, green and blue bands are obtained instead of a NIR, red and green bands. Whereas indexes such as the normalized different vegetation index (NDVI, Rouse et al., 1974) can not be determined without a red band, alternative vegetation indices such as the Green NDVI (Gitelson et al., 1996) have similar information content and value as NDVI. We demonstrate the camera, when mounted in a UAV, can be used to obtain leaf area index (LAI) of winter wheat at high spatial resolution.

MATERIALS AND METHODS

Camera System

The Fuji Photofilm Co., Ltd (Tokyo, Japan) FinePix S3 Pro UVIR camera (12 megapixels) does not have an internal NIR-blocking filter. Other digital cameras may be modified by removing this filter. A custom interference filter (Omega Optical, Inc., Brattleboro, VT) that blocks red light and transmits NIR (starting at 725 nm wavelength to avoid minor chlorophyll absorption from 700 to 720 nm, called the red edge) was mounted in front of the lens. The digital camera with filter was spectrally calibrated by taking photographs of monochromatic light from a SPEX 1680 monochromator (Jobin-Yvon, Edison, NJ) projected onto a Spectralon white panel (Labsphere, Inc., North Sutton, NH). The average digital numbers for the red/NIR, green and blue channels were determined for the brightest part of the projected light using image processing software (ENVI version 4.3, Research Systems, Inc., Boulder, CO).

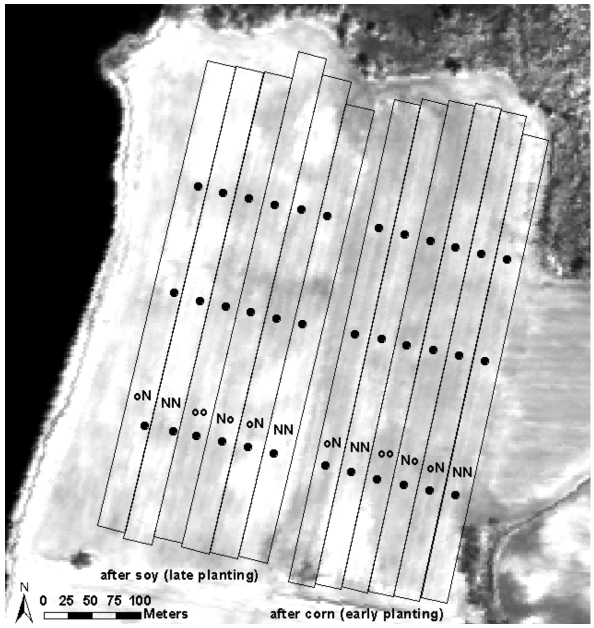

Figure 1. A georectified airborne AISA image (SpecTIR, Inc., Easton, MD) of winter wheat fields showing the various fall-spring nitrogen fertilizer treatments. The first letter shows the fall nitrogen application and the second letter shows the spring application, where "o" indicates no nitrogen and "N" indicates 34 kg/ha N. The east field was planted early following soybean and the west field was planted late following corn which created a large range in wheat leaf area index (LAI, sampled at points).

Field Test

Field experiments were established on two adjoining fields (Fig. 1), of approximately 10 ha each, located next to the Chester River on Maryland's Eastern Shore (39.03° N and 76.18° W). The eastern field was planted to winter wheat (*Triticum aestivum* L.) on 26 September 2006 following a corn (*Zea mays* L.) harvest. The western field was planted to wheat on 31 October 2006 following a soybean (*Glycine max* L.) harvest. Within each field, six 27-m wide strips running the length of the field were established, and were managed with one of four fertility treatments. Both fields were fertilized on 7 November 2006; alternating strips received either no fall fertilizer or 34 kg ha^{-1} N broadcast as pellets (Fig. 1). On 6 March 2007, four strips from each field were fertilized with 34 kg ha^{-1} N and the middle two strips were left unfertilized (Fig. 1). Due to a farm management error, the entire field was uniformly sprayed with an application of 68 kg ha^{-1} N fertilizer on 11 April 2007. Chlorophyll concentrations measured by pigment extraction and by Minolta SPAD-502 chlorophyll meter (Konica Minolta Sensing, Inc., Osaka, Japan) showed no significance differences among the various treatments (data not shown). Therefore, the only differences detectable in the field test were biomass and LAI. For field sampling, three plots were established in each treatment located in the southern end, northern end, and center of each north-south strip (Fig. 1). On 30 April 2007, LAI of each plot was measured using an LAI-2000 Plant Canopy Analyzer (LI-COR, Inc., Lincoln, NE, USA). Several other plots were acquired on an ad-hoc basis in areas of very low biomass and planter errors (double plant density), to increase the range in LAI.

The camera was mounted in a Vector P unmanned airborne vehicle (Fig. 2) and was controlled by computer navigation software to take photographs at user selected waypoints to insure complete coverage of the field. The UAV was flown at two altitudes, 400 feet (120 m) and 700 feet (210 m) above ground level on 2 May 2007. Tarpaulins of various colors (red, green, black, gray, and beige) were used to test the spectral and radiometric calibration of the camera (Hunt et al., 2005). Spectral reflectances of the tarpaulins were measured using an ASD FR Pro Spectroradiometer (Analytical Spectral Devices, Inc., Boulder, CO).

Figure 2. Vector-P unmanned airborne vehicle (UAV) manufactured by IntelliTech Microsystems, Inc. (Bowie, Maryland; http://www.vectorp.com).

The digital camera images were saved in Tagged Image File Format (TIFF) and imported into ENVI for processing. The digital numbers are affected by the solar spectral irradiance and the exposure settings of the camera. Therefore, the same pixel may have different digital numbers in different images, especially if the camera's exposure settings are automatically determined. Vegetation indices are a method for reducing the effects of irradiance and exposure, and enhancing the contrast between vegetation and the ground (Rouse et al., 1974; Gitelson et al., 1996). From Gitelson et al. (1996), the Green Normalized Difference Vegetation Index (GNDVI) is defined:

$$\text{GNDVI} = (\text{NIR} - \text{green})/(\text{NIR} + \text{green}) \quad [1]$$

where: NIR is the digital number of the Red/NIR channel with the red-blocking filter and green is the digital number of the Green channel. Because radiometric and spectral calibration will vary among digital cameras, the GNDVI from digital number was compared to the reflectance-based GNDVI for the colored tarpaulins. Because differences in irradiance are factored out in the index calculation, GNDVI (reflectances) were linearly related to GNDVI (digital numbers) with an R^2 of 0.99. Therefore, the correction equation was applied to all GNDVI calculated from digital numbers.

The digital camera had a variable time delay between the signal from the flight control unit and photograph acquisition; therefore, automated image registration was not possible. For the UAV flight at 700 feet (210 m), we located each plot accurately using the bare ground left from biomass determination, and calculated the average digital number for each band using ENVI.

RESULTS AND DISCUSSION

The spectral sensitivity of the camera showed that that the red/NIR channels on the Fuji FinePix S3 Pro UVIR camera had a significant response in the NIR (Fig. 2). The blue and green channels had very small responses in the NIR (Fig. 3). Above a wavelength of 800 nm, the responses of the three channels were about equal and at the noise level of the digital camera, so the principal response for the NIR band came from reflected radiation in the 700 nm-800 nm wavelength interval. Because the blue and green channels did not have significant sensitivity to NIR light (Fig. 3), the method of Ziglado et al. (2001) could not be applied to the digital camera used in this study to acquire NIR-red-green digital images.

A simple test with black-dyed paper will show if a digital camera's blue band is sensitive to NIR light because color-dyed paper is usually very reflective in the NIR. If the photographs show red, then the method presented here can be used to obtain NIR, green, and blue digital images. If photographs of black-dyed paper show either gray or white, then all three bands are sensitive to NIR, and the method of Zigadlo et al. (2001) could be used for color-infrared digital imagery.

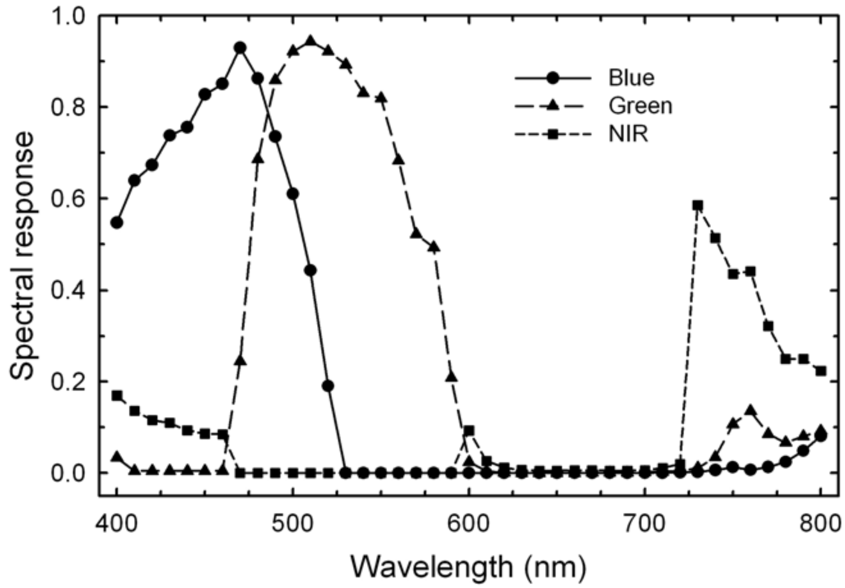

Figure 3. Relative spectral calibration of the Fuji FinePix S3 Pro UVIR camera for the blue, green, and red/NIR channels. A custom red-blocking filter was used to block photons (610 to 720 nm) from the red/NIR channel, so only NIR photons were detected.

The NIR, green and blue digital images acquired from the UAV (Fig. 4) are very similar to the NIR, red and green images acquired using color-infrared film. Because blue, green and red reflectances are all determined by the chlorophyll concentration in vegetation, the digital numbers on images from commercial cameras will go up and down together according to the absorption coefficient of chlorophyll (Daughtry et al., 2000; Hunt et al., 2005). For monitoring vegetation, the choice of NIR, red, and green bands for color-infrared photography is historical (e.g. Colwell, 1956). There may be some problems with haze that affects the blue band more than the red band; however, UAVs will usually fly close to the ground to acquire higher resolution imagery, so the effect of haze will be small.
From the focal length, the size of the camera lens, and the number of detector elements, the spatial resolution and the area covered by each photograph can be determined as a function of altitude above ground level (Table 1). For flights at 400 feet (122 m) and using a wide-angle lens (24 mm), the pixel size is about 2.7 cm and the area covered in one photograph is 0.91 ha. Flying at 30 m s^{-1} and assuming the time required to save one photograph is about 2.5 seconds, there will be no overlap between successive pictures. For flights at 750 feet (229 m) and the same speed, the wide angle lens will produce a pixel size of 5.1 cm, cover an area of 3.2 ha, and will have about 35% overlap between successive pictures. With this amount overlap, the individual photographs can be registered to obtain a complete image of a field. However, if very-high spatial resolution is required (pixel sizes < 2.5 cm), the photographs will be considered as plots obtained using a regular grid. Wind will affect the roll, pitch and yaw of UAVs and other aircraft, photographs from the digital camera system are easier to register with global positioning system and inertial guidance unit data compared to scanning sensors.

GNDVI showed strong differences in the amount of vegetation over the winter wheat field trials (Fig. 5). The values of GNDVI around the edge of the photograph are higher than values in the center for two reasons: first is lens vignetting and second is the oblique view angle through the wheat canopy. These factors can be reduced by using lens with a longer focal length, applying a statistical method to balance the digital numbers, or simply not using the pixels around the periphery of the image.

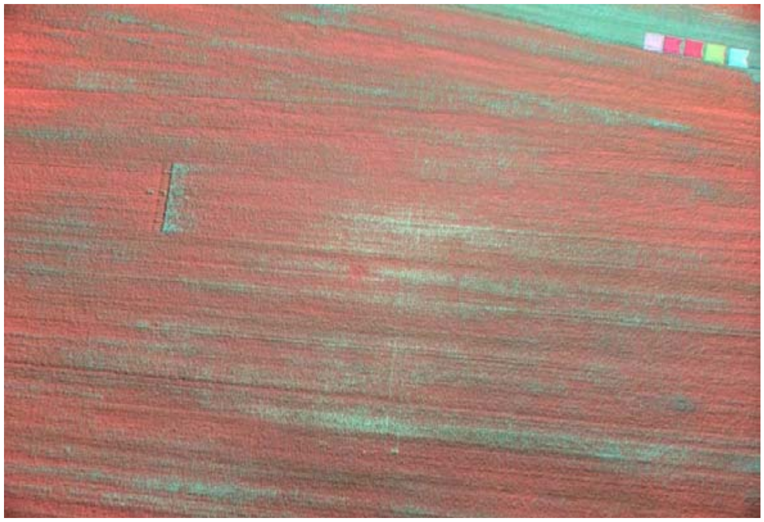

Figure 4. A near-infrared, green and blue digital image obtained from a small UAV flying at an altitude of 400 feet (120 m) above ground level. The near-infrared band is displayed as red. The two lines running from top to bottom in the center of the image are footpaths where the wheat was trampled slightly on the way to a sample plot. The squares along the top are colored tarpaulins used to calibrate GNDVI from digital numbers to reflectances.

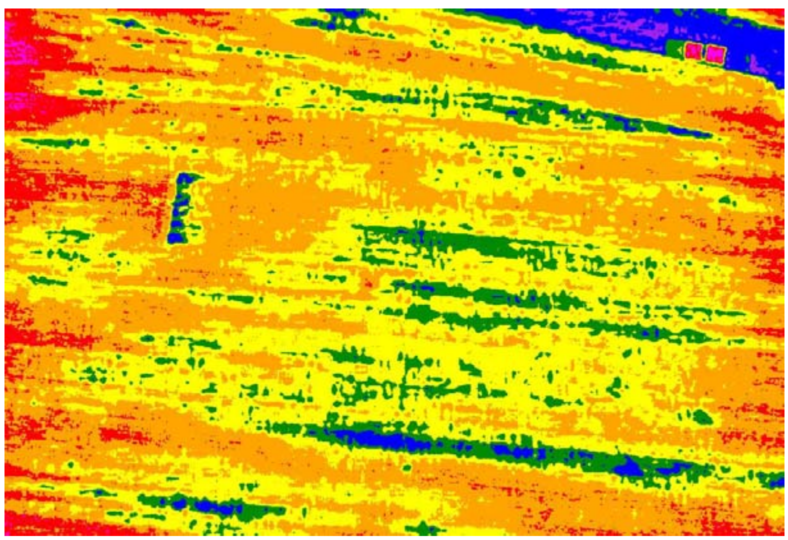

Figure 5. Variation of green normalized difference vegetation index (GNDVI). The amount of vegetation is shown by the color (purple 0.00-0.50, blue 0.50-0.57, green 0.57-0.64, yellow 0.64-0.71, orange 0.71-0.78, red 0.78-0.85, magenta 0.85-1.00). Higher values of GNDVI occur around the edges of the photograph because of lens vignetting and more oblique view angles.

Table 1. Pixel size and coverage area for the 12-megapixel Fuji FinePix S3 Pro UVIR digital camera at two altitudes (above ground level) and for two lens-focal lengths.

		Focal length 24 mm		Focal length 55 mm	
Altitude (feet)	Altitude (m)	Pixel size (cm)	Area (ha)	Pixel size (cm)	Area (ha)
250	76.2	1.7	0.36	0.75	0.068
400	122	2.7	0.91	1.2	0.17
500	152	3.4	1.4	1.5	0.27
750	229	5.1	3.2	2.2	0.61
1000	305	6.9	5.7	3.0	1.1
1500	457	10.3	12.8	4.5	2.4
2000	610	13.7	22.8	6.0	4.3
2500	762	17.1	35.6	7.5	6.8
3500	1067	24.0	69.9	10.5	13.3
5000	1524	34.3	143	15.0	27.2

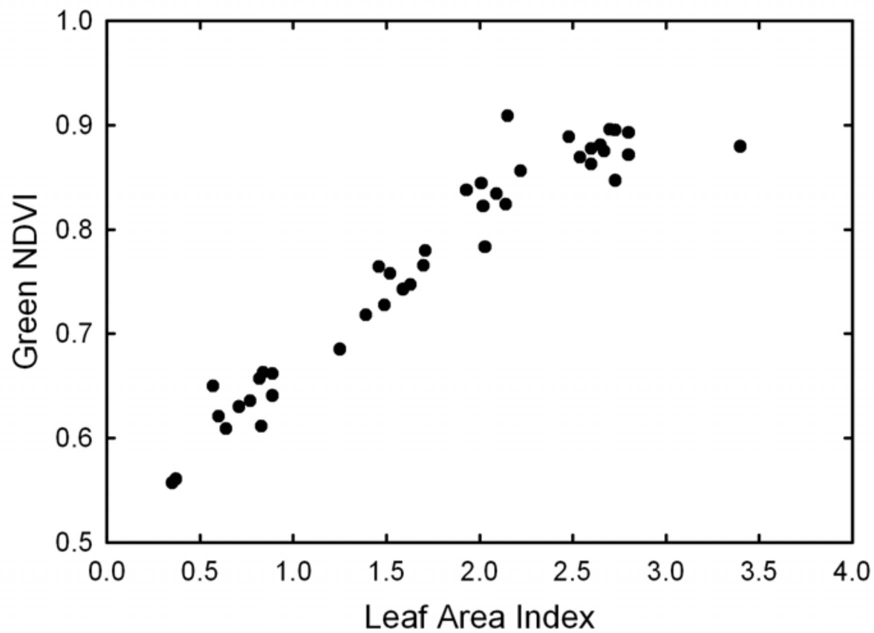

Figure 6. Relationship of GNDVI with leaf area index (LAI) in winter wheat. For LAI from 0 to 2.5 $m^2 m^{-2}$, the regression equation is GNDVI = 0.5 + 0.16 LAI, with an R^2 of 0.85.

GNDVI was linearly related to LAI up to 2.5 $m^2 m^{-2}$ (Fig. 6). Above an LAI of 2.5 $m^2 m^{-2}$, GNDVI was not responsive to changes in LAI. Most vegetation indices saturate at some level of LAI (Daughtry et al., 2000), so the response of GNDVI to LAI was expected (Fig. 6). Gitelson et al. (1996) developed the GNDVI for determining the plant chlorophyll status, which is strongly related to nitrogen status in wheat (Hinzman et al., 1986) and other stress factors. Shanahan et al. (2001) showed that GNDVI had the highest correlation with corn grain yield. UAVs with the camera system presented in this study may be useful for within-season crop management in site-specific agriculture or precision farming.

Whereas the camera system presented here was developed for crop nitrogen management from UAVs, the resulting NIR-green-blue images can be used for other vegetation monitoring and can be used on other platforms similar to the standard NIR-red-green color-infrared photography. The camera with an improved GPS system is being flown in manned aircraft for invasive weed detection and forest management. Furthermore, NIR, green and blue digital images can be acquired using pole-mounted cameras for ground-based determination of plant cover using image processing programs such as ENVI or VegMeasure (Johnson et al., 2003). The first principal advantage of the NIR-green-blue digital camera system is that post-processing is not required for the digital images, in contrast to photographs obtained using the method of Zigadlo et al. (2001), so the images can be visually inspected straight from the camera for the amount and type of vegetation. The second principal advantage is the relatively low cost of the system, because the silicon diode charge-coupled detectors in digital cameras are already sensitive to NIR light. Cameras such as the Fuji FinePix S3 Pro UVIR camera are sold without the internal NIR-blocking filter, so some cameras do not have to be modified.

The advantage of UAVs is the ability to fly small areas in between weather events, such as rainstorms during the late spring or early summer, in order to acquire useful imagery within a short window of time. With rapid growth of crops, there is only a small window of opportunity for fertilizer needs to be estimated (two weeks for corn), usually when crop cover is only 10-20%. Under these conditions, soil reflectance dominates canopy reflectance in large pixels. However, with very high spatial resolution, pixels in which soil reflectance dominates can be masked out, and only the pure crop pixels could be used to estimate crop nitrogen requirements (Scharf and Lory, 2002).

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