ULTRA LOW LEVEL AIRCRAFT (ULLA) AS A PLATFORM FOR ACTIVE OPTICAL SENSING OF CROP BIOMASS

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ABSTRACT

Crop producers requiring crop biomass maps to support timely application of in-season fertilisers, pesticides or growth regulators rely on either on-ground active sensors or airborne/satellite imagery. Active crop sensing (for example using Yara N-Sensor^{TM}, Greenseeker^{TM} or Cropcircle^{TM}) can only be used when the crop is accessible by person or vehicle, and extensive, high-resolution coverage is time consuming. On the other hand, airborne or satellite imaging is often hampered by cloud, either in the sensor-image path or by associated non-uniform illumination of ground targets. We have combined the desirable attributes of active optical sensing with the fast, synoptic coverage afforded by aircraft platforms. An ultra low-level aircraft (ULLA) system carrying an active NIR/Red CropCircle^{TM} sensor was successfully deployed at an altitude of 3-5 m over a 270 Ha field of skip-row sorghum (*Sorghum bicolor*) to measure and map crop vigour via the simple ratio (SR) index. A comparison to a SR map derived from a meter-resolution airborne digital image was found to reproduce the spatial variability observed in the image of the field. As the sensor contains its own light source, it can be operated irrespective of ambient light conditions. It is relatively cheap, lightweight, small in size and can easily be retro-fitted to aircraft. The ULLA active sensor approach offers crop managers a viable alternative to conventional imaging technologies especially when they have day-to-day access to aircraft already conducting low-level operations, for example crop dusting and reconnaissance, over their agricultural fields. Furthermore, extensive on-ground work worldwide to calibrate active optical sensors to crop N-status/recommendations means whole-of-field N status/recommendation maps can now be rapidly generated using the same sensors mounted in aircraft.

Keywords: active optical sensor, CropCircle, simple ratio index, photosynthetically-active biomass (PAB), ultra low-level airborne (ULLA)

INTRODUCTION

Numerous reviews have been written illustrating the breadth of research and development activity and challenges faced by airborne and spaceborne remote sensing technologies in support of precision agriculture (for example Brisco et al. 1998; Bastiaanssen 2000; Lamb 2000; Moran 2000; Lamb and Brown 2001). Satellite imagery provides large scale coverage (tens to hundreds of square kilometers) and a number of current multispectral systems, for example IKONOS (Cook et al. 2001) and Quickbird (Wenzhong and Shaker 2004) provide meter (multispectral channels), if not sub-meter (for example Quickbird panchromatic channel) spatial resolution. Hyperspectral satellite imaging systems, for example the Hyperion imaging spectrometer onboard the EO1 satellite (Ungar et al. 2003) provides greater spectral resolution, but generally poorer spatial resolution. Large spatial coverage keeps the per hectare costs of imagery low, an attractive proposition for end-users although commercial viability from a provider's perspective requires large numbers of end-users be sourced within the image footprint.

Airborne imaging systems, both multispectral and hyperspectral have appeared over agricultural fields, by and large to fill perceived operational gaps in the performance of satellite image systems; providing greater spatial resolution for a given set of spectral performance criteria, user-defined spectral and spatial resolution, the ability to operate only over targets of interest (occupied by paying customers), increased operational flexibility in terms of capitalizing on weather and imaging conditions, for example their ability to operate under high cloud base (Lamb 2000) as well as being able to coincide with on-ground support activities (for example in support of image calibration).

Of all the parameters sensed by multispectral or hyperspectral imaging systems in agriculture, simple canopy indices that utilize the reflectance of plant canopies in the near infrared (NIR; ~770-1500 nm) and red (Red; ~630-680 nm) wavelength ranges (bands) dominate. These include, for example the normalised difference vegetation index, $\mathrm{NDVI} = \frac{\mathrm{NIR - Red}}{\mathrm{NIR + Red}}$ (Rouse et al. 1973), simple ratio, $\mathrm{SR} = \frac{\mathrm{NIR}}{\mathrm{Red}}$ (Jordan 1969) and soil adjusted vegetation index, $\mathrm{SAVI} = \left(\frac{\mathrm{NIR - Red}}{\mathrm{NIR + Red + L}}\right)(1 + \mathrm{L})$ (Huete 1988). Useful discussions of the relationship between individual bands and derived indices and vegetation fraction and leaf pigments can be found in Gitelson et al. (2002; 2003) and recent reviews of multispectral indices for crop disease and vigour detection can be found in Huang et al. (2007) and Devadas et al. (2009). Not only do the simple indices described above exhibit utility in mapping spatial variability in biophysical descriptors such as plant leaf area index (LAI), photosynthetically active biomass (PAB) and chlorophyll content, with potential ability to correlate to crop yield and/or quality, but the broad-band, multi-spectral imaging systems necessary to collect data in these wavebands are relatively simple.

After almost 25 years of sensor research and development, and the proliferation of commercial image providers offering services to agricultural land managers, timely service delivery remains challenged by the need to match the availability of aircraft, pilot, and system operator, when weather and in-field conditions (including crop phenology, pest incursion, disease outbreak) and/or the availability of on-ground agronomic support staff are aligned. In Australia, the interval between request and acquisition or delivery of image products can range from one week to one month although this may be offset by advanced booking, in particular when it comes to scheduling for, say, crop anthesis. However use of derived map products for application of insecticides, foliar nutrients or growth regulators requires a considerable degree of scheduling flexibility which still challenges some image providers. Even when these factors fall into place it is not uncommon for scheduled imagery to be limited by climatic events such as low cloud.

Image calibration standards vary from provider to provider; some imagery is delivered calibrated to at-sensor radiance while others use raw digital numbers. Very few providers deliver imagery calibrated to on-ground reflectance values, unless the scope of the project (and hence cost) includes the additional on-ground work required to establish calibrated reflectance targets within the image field of view. The use of at-sensor radiance or sensor-generated digital numbers distort the values of derived band ratios compared to those measured using on-ground reflectance values because the spectral information 'arriving 'at an overhead sensor will be influenced by the atmospheric path traveled by the incident radiation (Chavez 1996; Edirisinghe et al. 2001) or the sensor gain and offset values which governs the production of electrical signals from the sensor in response to incident photons. Between target and sensor, the radiation is influenced by a number of wavelength-dependent factors including scattering, absorption and refraction. Scattering of additional radiation into the field of view of the sensor is generally considered an additive effect whilst transmission effects (absorption and scattering out of the field of view) is considered a multiplicative effect (for example refer to references cited within Chavez, 1996). A considerable amount of work has been conducted to investigate the effect of path radiance effects on airborne remotely sensed imagery and to correct such imagery in order to reproduce at-ground reflectance values for targets (for example Edirisinghe et al. 2001).

The development of portable, hyperspectral, field radiometers that rely on reflection of ambient light from crop canopies was initially motivated by the requirement to calibrate overhead at-sensor radiance measurements to on-ground, plant canopy reflectance. However passive, hyperspectral radiometers have also been used in their own right to measure biophysical descriptors in crops (for example Huang et al. 2007 and references within).

More recently, active multispectral sensors have been developed for on-ground use (Künnemeyer et al. 2001; Middleton et al. 2004; Holland et al. 2004; Inman et al. 2005). The key advantages of these sensors is that they contain their own light source and if used in conjunction with synchronous detection, can be operated irrespective of the ambient light conditions (including at night). Also, if the ratio of two wavebands are used, and the optical, sensor-target characteristics of each source are the same, then derived band ratios are absolute, not distorted by path radiance effects and insensitive to meter-scale variations in sensor-target distances so long as they are operated within the linear, optical response range of the internal sensors. Utilizing both Red and NIR wavebands to create NDVI or similar indices, these sensors are finding a range of in-crop manual or vehicle applications including on-the-go nitrogen top-dressing (Inman et al. 2005; Solaria et al. 2008), weed spraying (Sui et al. 2008) and biomass estimation (Künnemeyer et al. 2001; Flynn et al. 2008; Trotter et al. 2008).

There is a distinct opportunity to combine the desirable attributes of on-ground, active R/NIR sensors, including their relatively low cost, compact size and low weight, with the ability of low-flying aircraft to cover large tracts of ground very quickly, especially those aircraft normally over-flying the crops of interest during field scouting and crop-dusting. Consequently, this paper describes the assembly, deployment and preliminary evaluation of an active, on-ground, R/NIR plant canopy sensor in an ultra-low level aircraft for recording and mapping crop vigour via the simple ratio (SR) index.

MATERIALS AND METHODS

The Sensor

The sensor selected for the trial was the CropCircle™ ACS210 (Holland Scientific, Lincoln NE USA), 'red head', coupled to a Geoscout 400 datalogger (Holland Scientific, Lincoln NE USA). This sensor emits radiation from light emitting diodes (LEDS) with peak emission wavelengths at 650 nm and 880 nm (Holland et al. 2004). The LED-lens configuration provided an approximately collimated beam with a source-ground footprint divergence angle of approximately 32^{o}x 6^{o}, or when orientated with the long-axis at right angles to the direction of travel, a footprint of approximately (0.57 x sensor altitude AGL) and (0.11 x sensor altitude AGL) across and along the direction of travel, respectively (Holland Scientific 2004).

A simple laboratory test involving measuring the CropCircle™ output with increasing distance from a homogenous target (> 1 m) confirmed that the individual Red and NIR signal output from the detectors followed an inverse power law with increasing source-target distance whereas resulting NDVI and SR values appeared invariant for distances up to 6.5 m (Lamb et al. 2009). These results set an effective upper-limit of ~ 6 m to the operating altitude of the sensor above the crop canopy.

The CropCircle sensor was mounted in a nadir-viewing configuration underneath a Fletcher FU24954 (VH-EQC) crop-dusting aircraft (Figure 1) with the long axis of the source LEDS orientated at right angles to the forward direction of the aircraft. The datalogger was attached inside the cockpit to allow the pilot to trigger the recorder at the commencement and completion of the acquisition process.

Figure 1. Photograph of the Fletcher FU24954 (VH-EQC) crop-dusting aircraft and the CropCircle mount (inset). The sensor was positioned in a nadir-view configuration with the long-axis of the LED array at right angles to the flight direction.

Positional information was provided from a 5 Hz global positioning system (Garmin GPS18 x 5 Hz, Olathe, Kansas USA); a low-cost GPS sensor for use agricultural applications. The GPS-datalogger configuration used allowed for a dynamic interpolation of the 5Hz location/velocity records to provide an effective 20 Hz position calculation rate in the datalogger. Whilst the sensor head provides an optical ouput signal at 200 Hz, Red and NIR reflectance values were recorded at approximately 20 Hz to coincide with positional records interpolated from the GPS data string.

The field site and data acquisition

The active optical sensor evaluation was conducted over a 270 ha field of grain Sorghum (*Sorghum bicolor*) located at Collymongle Station , northwest New South Wales, Australia (Lat 29^{o} 25' S, Long 148^{o}53' E). The sorghum was planted in a skip-row configuration (2 m- 2 row raised bed, 2 m skip-row) with rows orientated WNW-ESE and at the time of sensor evaluation the crop was between stages 5 (boot stage) and 6 (half bloom) (Vanderlip and Reeves 1972).

Crop biomass measurements were conducted at 17 locations within the field, the location of each was recorded using a differential global positioning system (DGPS, Trimble, Sunnyvale California). On-ground measurements of SR was acquired using a second hand-held CropCircle unit by walking 8, parallel, across-row transects within a 10m x 10 m region centred on the recorded dGPS position. The on-ground Cropcircle sensor records were collected at a minimum rate of 1 Hz, and the walking pace maintained constant at approximately below 1 ms^{-1} to ensure a consistent proportion of crop row and skip-row coverage. The SR value was calculated from each of the Red and NIR sensor records and averaged over the 10 m x 10 m region. Crop samples were subsequently collected by cutting to ground level, 3 x 1 m-long row segments selected at random within the 10 m x 10 m region. The samples were oven dried at 40^{o}C, weighed, and weights converted to kg of dry matter per ha (kg DM/ha).

The ultra low-level airborne (ULLA) sensor was flown on 17th December 2008 between 9.30 am and 10.30 am local time (Australian Eastern Daylight Savings Time- AEDT). Sensor data was collected at an altitude of 3-5 m above ground level (AGL) in NNE-SSW transects (at right angles to the crop rows), spaced 20 m apart and at a speed of 40 m s^{-1} (approximately 80 knots indicated airspeed). At a mid-range sensing altitude of 4 m AGL, the CropCircle footprint on the crop canopy measured approximately 2.3 m across x 0.5 m along the direction of travel. Instantaneous sensor Red and NIR reflectance values were used to calculate the SR. The ULLA sensor point data was block kriged using a 25 m block size and an exponential semi-variogram model using the computer program Vesper (Whelan et al. 2001) and then re-sampled to a 10 m grid.

For the purposes of comparison, a digital image of the same field was acquired on the same day, using SpecTerra Service's digital multispectral airborne imaging system, a four band, frame transfer-type imaging sensor. Whilst the sensor contained 4 available image channels, only the 677 nm (Red, bandwidth 18 nm) and 781 nm (NIR, bandwidth 20 nm) wavebands were subsequently analysed. Imagery was acquired at an altitude of 1800 m AGL to provide a spatial resolution (pixel size) of approximately 1 m. The images were acquired at 8:48 am local time, equating to a solar zenith angle of 56^o, and azimuth angle of 98^o. Individual frames of image data were corrected using SpecTerra Service's proprietary sensor geometric and radiometric techniques. Given the ±14^o field of view of the imaging system, the slope of the bidirectional reflectance distribution function (BRDF) surface for the Red and NIR bands were observed to be very similar, meaning that calculation of the SR image from the ratio of the Red and NIR image bands was deemed sufficient to remove the BRDF from the SR image (Dr Frank Honey, SpecTerra Services, Personal Communication 2009). The SR image was finally re-sampled image to a 10 m grid.

RESULTS AND DISCUSSION

An investigation of the logged ULLA sensor data showed the datalogger recorded the GPS/CropCircle data at approximately 17 Hz rather than the expected 20 Hz. A plot of the SR values returned from the ULLA sensor for a 633 m segment of a transect is depicted in Figure 2. This length of segment includes 158 skip-rows with a data sampling interval of 2.4 m along the direction of travel. The physical spacing of sampled data points (2.4 m) compared to the crop and skip-row interval (2 m) immediately suggests the existence of a Moiré effect resulting from the beating of the sensor sampling and skip-row frequencies (Kafri and Glatt 1990). For an aircraft forward speed of 40 m s^{-1} this equates to a beat frequency of $\approx$ 3 Hz, or every 6 data points. The sensor footprint of 0.5 m in the forward direction of motion, coupled with the deflection of the footprint resulting from small attitude changes in the aircraft may reduce the contrast between the crop and skip-row response. The frequency distribution of the SR values for each sensor (Figure 3) are consistent with this; the airborne sensor-derived SR values exhibit a normal distribution (Figure 3a) while the ULLA sensor values are slightly skewed towards the higher SR values (Figure 3b). The 2.4 m sampling resolution of ULLA sensor will always result in a lower number of bare soil records in the available clear skip-rows compared to the 1 m resolution of the imagery.

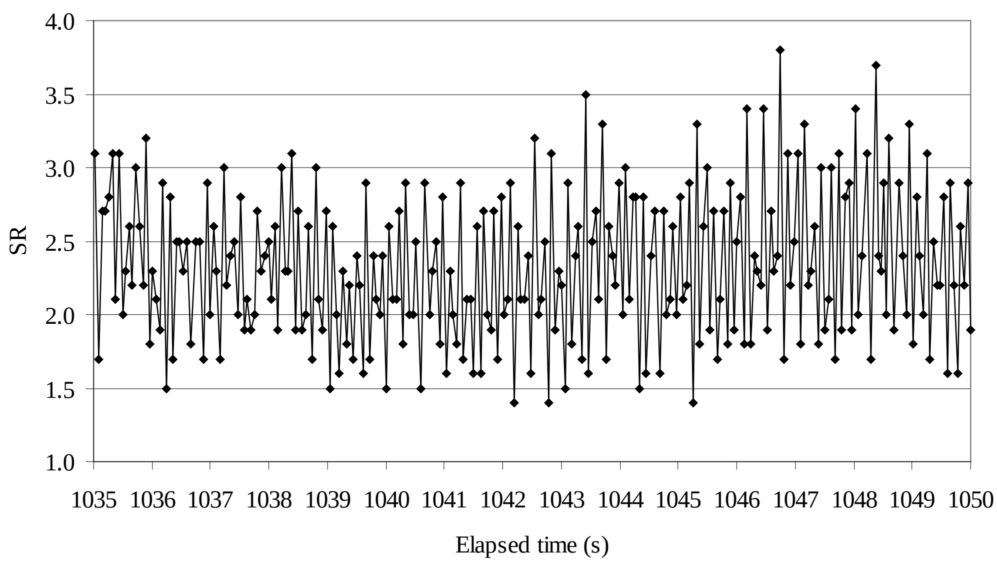

Figure 2. Sequence of SR values recorded from a 633 m long segment of a transect.

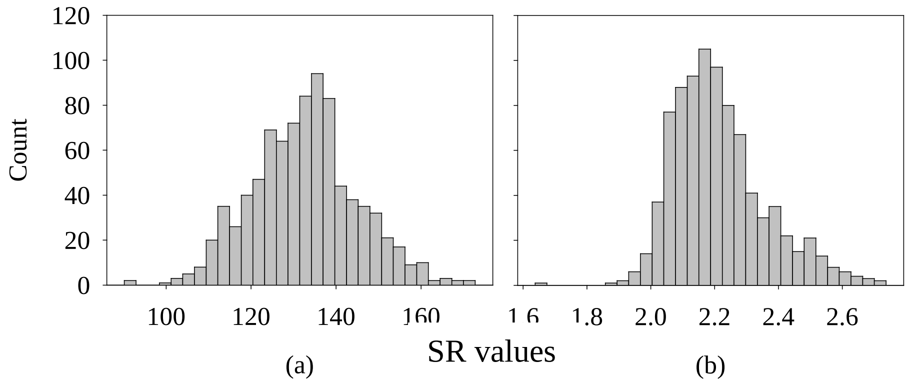

Figure 3. Frequency distribution histograms for the (a) multispectral image-derived SR values (re-sampled to 10 m grid) and the (b) ULLA-SR values (block kriged using 25 m block then re-sampled to 10 m grid).

A scatterplot of SR values as a function of biomass (kg DM/ha) is given for each of the on-ground and ULLA CropCircle sensors, and for the 1 m resolution airborne multispectral image (Figure 4). Here the block kriged, ULLA sensor, point data was re-sampled to a 10 m grid and the SR value coincident with dGPS plot location was extracted. The airborne digital SR values were similarly extracted from dGPS location by re-sampling image to a 10 m grid and extracting the coincident point SR value.

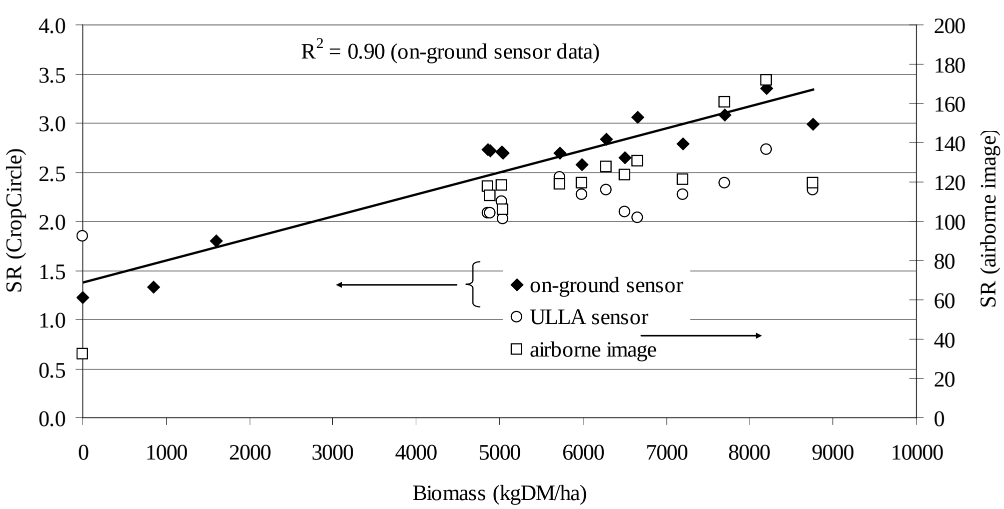

Figure 4. Scatterplot of SR versus biomass (kg DM/Ha) for each of the on-ground and ULLA CropCircle sensors (kriged data re-sampled to 10 m grid), and for the 1 m resolution multispectral airborne image re-sampled to 10 m grid.

The most obvious feature of Figure 3 is the fact that the SR values for the on-ground and ULLA sensors are completely different to those extracted from the airborne multispectral image. The ULLA and on-ground sensor data are absolute ratios based on the active light sources contained within the CropCircle units and these have been observed to be invariant with sensor target distances from 1 to 6 m (Lamb et al. 2009). The airborne image-derived SR values are derived from the conversion of at-sensor brightness values to DN- here a function of the gain and offsets of each of the cameras used in the sensor. Effectively the airborne image-derived SR values, in the absence of any DN/on-ground reflectance calibration are arbitrarily scaled. Notwithstanding the scaling issues, all sensors appear to record a linear increase in SR values with increasing biomass, for example $R^2 = 0.90$ for the on-ground sensor (Figure 4). Much of the scatter in these plots, especially those from the ULLA sensor and airborne imagery, is attributed to the method by which point or pixel data were processed to a 10 m grid. The ULLA sensor SR values appear less sensitive to increases in biomass (Figure 4). This is most likely due to the fact that the ULLA point data was kriged to a 25 m grid prior to re-sampling, resulting in an elevated the SR for the bare soil calibration location (0 kg DM/ha).

A PAB map created from the ULLA sensor log is given in Figure 5, along with the PAB map created from the 1 m resolution digital multispectral airborne image. Here the block-kriged ULLA data is re-sampled to a 10 m grid and the airborne image-derived SR map, the image also re-sampled to the same 10 m grid.

The gross spatial variability features in the ULLA-PAB map appears similar to that of the airborne image-derived PAB map, although the higher spatial resolution of the original airborne image (1 m) compared to the 25 m block kriging used for the ULLA point records is evident in the 'graininess' of the image-derived map. There is a region in the lower right quadrant of the ULLA-PAB map that appears to have noticeably higher SR values than the corresponding image-derived PAB map. Following the earlier discussion regarding the spatial sampling resolution of the two sensors, the Moiré effect in ULLA sensor records may have produced elevated SR values compared to the imagery. However it should also be recognized that the multispectral image of the field was created from a mosaic of four image frames and one of the mosaic seams exists in this region; this small discrepancy may have arisen during the process of mosaicing the reference imagery together. The acquisition of the multispectral imagery used in this work was timed to ensure the solar zenith angle exceeded the field of view of the sensor, thereby reducing BRDF effects, and ultimately avoiding the need to apply a correction process over and above simply calculating the SR. However, other commercial image providers may not have such flexibility or experience, and taken with all the scheduling considerations discussed earlier, it is possible that acquired imagery may suffer from, and require additional correction for, BRDF effects which will likely be crop- as well as phenology-specific. The active optical sensor approach, involving a nadir-viewing sensor moving over the top of the crop, is not influenced by such BDRF effects, nor any potential distortion of values resulting from the mosaicing of high-spatial resolution image frames together.

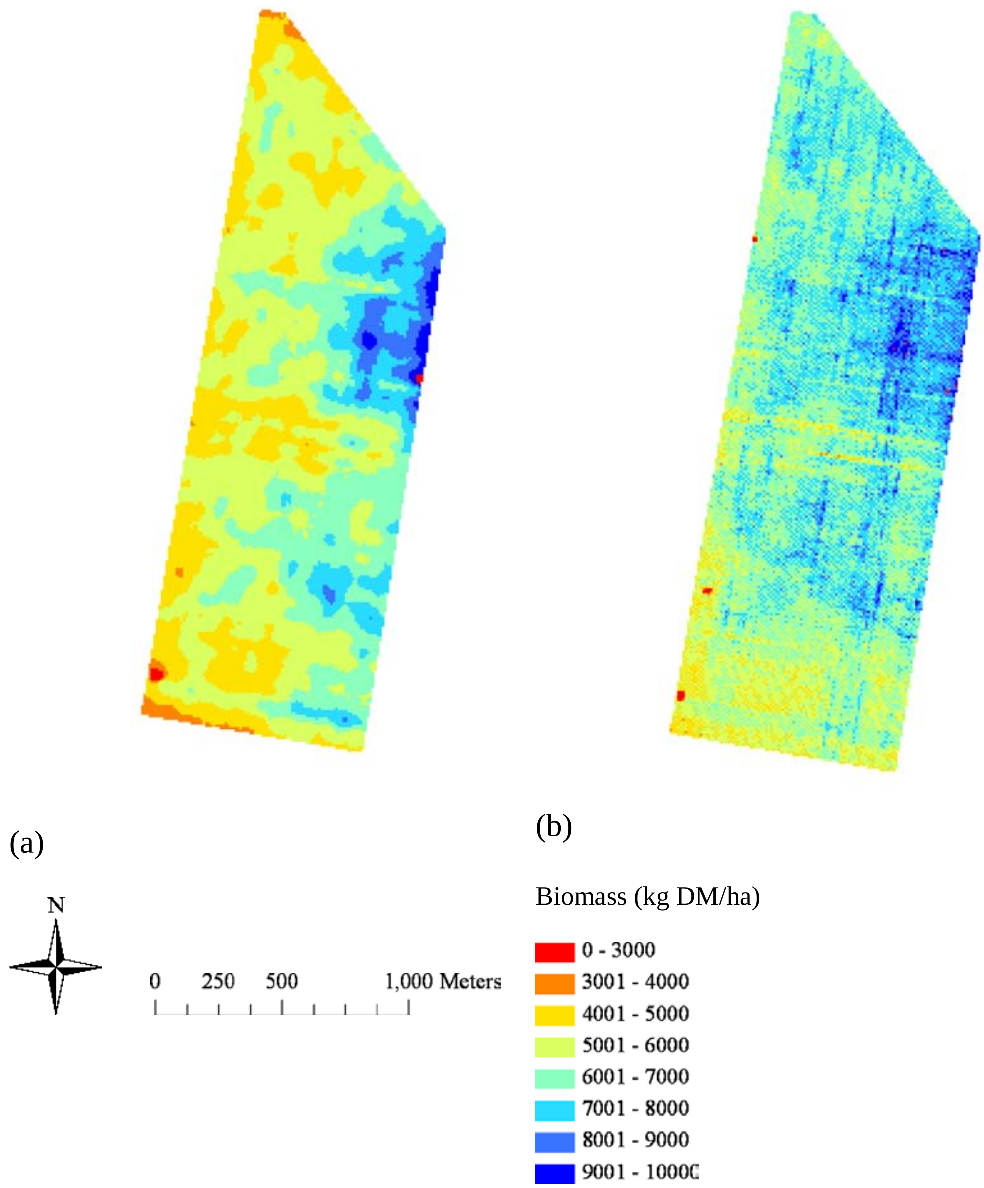

Figure 5. Biomass maps rendered by (a) block kriging the ULLA point SR data using a 25 m block size and an exponential semi-variogram model, and then re-sampling to a 10 m grid, and (b) re-sampling an airborne digital SR image to a 10 m grid..

At 40 ms^{-1}, and flying 20 m transects, the ULLA sensor surveyed the entire 270 ha field in approximately 1 hour. An airborne imaging system with a 2 km x 2 km image footprint could cover up to 300 - 350 square kilometers of survey in this same period if there is sufficient area to fly, and depending on the contiguity of the target areas (Dr Frank Honey, SpecTerra Services, Personal Communication 2009). Thus, practical applications of the ULLA, active sensors remain limited by the speed at which they can be flown. The real advantages of the ULLA active sensors is that they are relatively inexpensive (~US$5,000), lightweight (<400 g) and generally small in size (~500 cm^3), making it possible to retro-fit them to the outer shell of agricultural aircraft and allowing 'piggy-back' deployment during other low-level agricultural operations, for example crop-dusting.

CONCLUSIONS

An ultra low-level aircraft (ULLA) carrying an active NIR/Red CropCircle^{TM} sensor was successfully deployed at an altitude of 3-5 m over a 270 ha field of skip-row sorghum to record and subsequently map photosynthetically active biomass (PAB) via the simple ratio (SR) index. A comparison of the 2-D ULLA-PAB map derived from 20 m transects was found to reproduce the gross features of a PAB map derived from a meter-resolution airborne digital multispectral image re-sampled to a similar spatial resolution. Using a relatively low-cost GPS, it was possible to log SR/GPS records at a frequency of 17 Hz. The Moiré effect resulting from the difference between the sampling frequency of the ULLA sensor and the 2 m skip-row interval reduced the proportion of bare-soil skip-rows sensed compared to that appearing in the multispectral image, slightly modifying the distribution of the SR values derived from each sensor. Nonetheless, the ULLA-PAB map did reproduce the gross spatial variability observed in the PAB map derived from the airborne multispectral image of the field.

These sensors are active hence can be operated irrespective of ambient light conditions and at night, are of relatively low cost, lightweight, small in size and can easily be retro-fitted to the outer shell of aircraft, requiring only a hole large enough to allow a cable to pass through into the cockpit. Consequently active ULLA sensors provide farm managers an alternative to conventional imaging technologies especially when involving aircraft already conducting low-level operations, for example crop dusting and reconnaissance, over agricultural fields.

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