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Characteristics of consumer-grade cameras for multi-spectral vegetation monitoring with ultra-light UAVs

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Consumer-grade cameras (CGC) have advantageous characteristics for close-range vegetation monitoring, although there are limitations for many scientific applications [1]. We discuss four categories of constraints, as well as potential modifications for effective vegetation monitoring.

(I) Color Filter Array

A subsampling technique known as a color filter array (CFA) defines the spectral sensitivity of CCD/CMOS sensors in CGCs [2]. This involves a physical construction whereby each pixel element measures a portion of the spectrum (Fig. 1) and poses a hard constraint on the spectral acceptance of the three available bands.

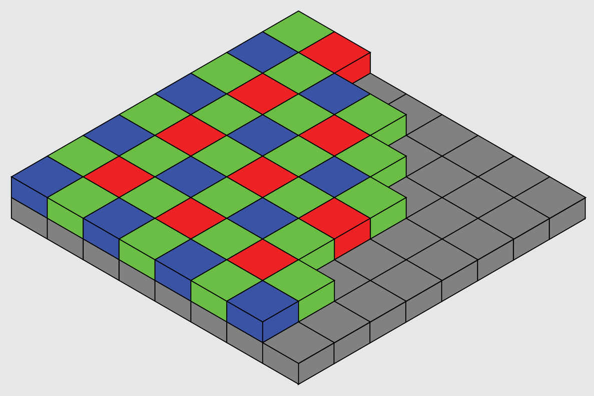

Figure 1 The Bayer pattern is the most common color filter array in consumer-grade cameras. Source: Colin M.L. Burnett (creative commons license BY-SA 3.0).

(II) Optical Filters

To obtain true-color photos, the sensitivity is further tuned using a hot-mirror optical filter that only allows the visible part of the spectrum to pass. Unlike the CFA, this filter can be removed without modifying the sensor and can be replaced by a band-pass or long-pass filter to achieve (additional) UV or NIR sensitivity of one or more spectral bands. The CFA, however, prevents separation of red and NIR, which are commonly used for vegetation indices. We therefore operate a UAV [3] with two filter setups (Fig. 2).

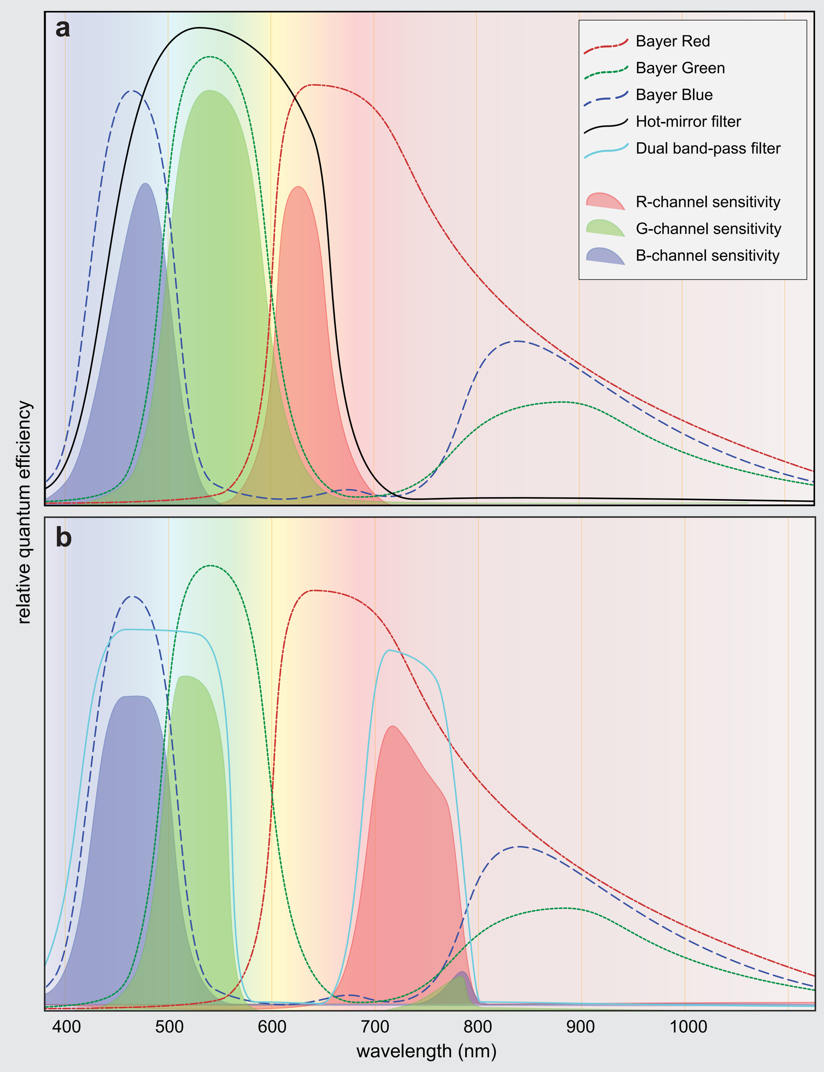

Figure 2 Approximate spectral response curves of two filter setups. **a:** original true-color R,G,B camera and **b:** the same camera with a dual band-pass filter that yields NIR,G,B sensitivity. Modified after Figure 4 in [1].

(III) Sensor Radiometry and Spatial Heterogeneity

CGCs are fitted with silicon-based CCD or CMOS sensors and therefore use the same technology as common mapping cameras and imaging spectrometers for the visible and NIR spectral range [4]. There are, however, two sensor issues that need to be accounted for if CGCs are used for spectral measurements. In a laboratory setup (Fig. 3) we addressed these issues.

Vignetting causes a non-uniform sensor response across the field of view

Lab photos illustrate this effect that is caused by the alignment and quality of the lenses (Fig. 4). As a result, pixel values decrease with distance from the scene center, while illumination conditions remain constant. We compensated for this by flat-field correcting the raw data [5], which effectively removed the vignetting and left a minor spatial gradient.

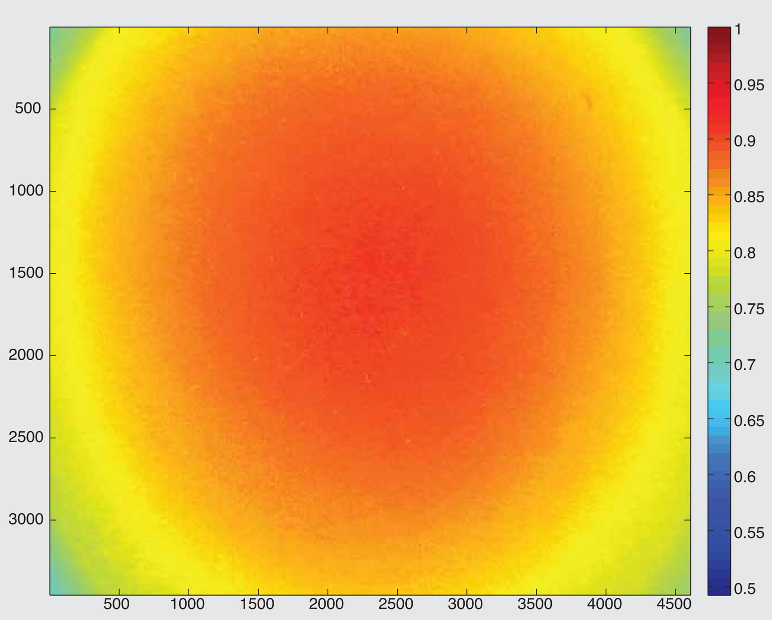

Figure 4 Vignetting mask derived from laboratory images and used for flat fielding. Both axes: pixel number.

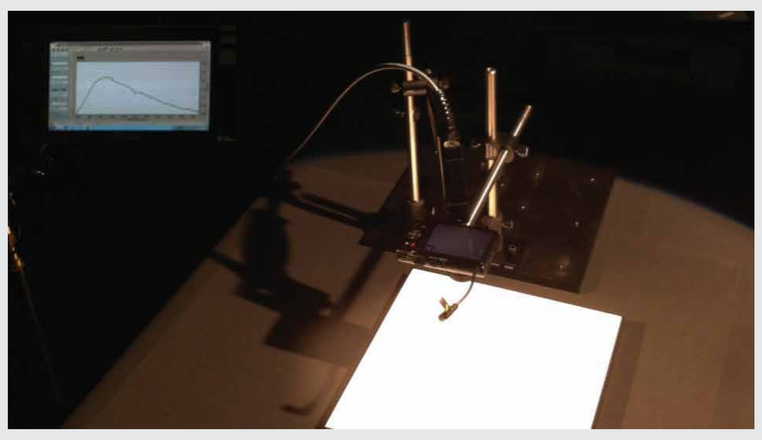

Figure 3 Laboratory setup. We used a Quartz-Tungsten halogen lamp (Oriel QTH) with a Köhler illuminator, a Spectralon panel for lambertian reflection and an ASD 4 Field-Spec Pro for spectral measurements. The cameras are Canon Ixus 125 HS with 16.1 mega-pixel CMOS sensor. Camera settings were empirically fixed to match the most common operational values under clear-sky conditions: widest zoom, ISO 100 and *f* 2.7. Linearity of the integration time was tested and confirmed (data not shown) and for radiometric calibration fixed to 1/640 sec.

The recorded digital numbers do not represent radiation energy

We tested the relationship between digital numbers (DN) and radiance (L) for common operational camera settings. A second-order polynomial effectively described the relationship and holds for the range of integration times (1/1000s - 1/200s), which appeared linearly related to DN. Fig. 5 shows the function which was used for radiometric calibration of the NIR channel.

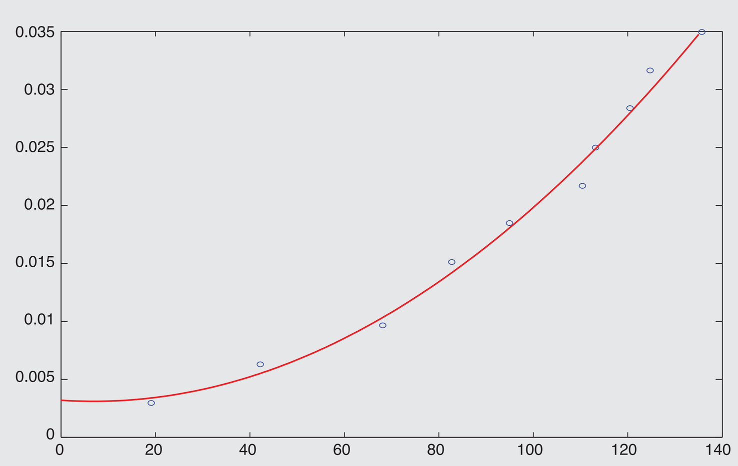

Figure 5 Radiometric calibration curve for the NIR channel. x: digital number (DN), y: radiance (L) in W/sr/m²/mm.

(IV) Dynamic Illumination Conditions

Variations in illumination, in combination with automatic exposure settings, dictate the use of calibrated reflectance values for multi-temporal analysis and the derivation of biophysical parameters. This is not commonly possible for CGCs acquisitions. It renders single-band metrics, like infrared intensity, inadequate and nominates indices as proxies to vegetation parameters [1]. Conventional red-edge based indices, however, need to be calculated from (I) a two-camera system, (II) two coregistered flights with different filter setup or (III) alternative spectral bands. The third option includes using blue as substitute for red, e.g. (NIR-B)/(NIR+B), or using visible bands only, e.g. excess greenness (2G-R-B) or green chromatic coordinate (G/RGB). Series of field images over an agricultural test site illustrate the use of options II (Fig 6c) and III (Fig 6d).

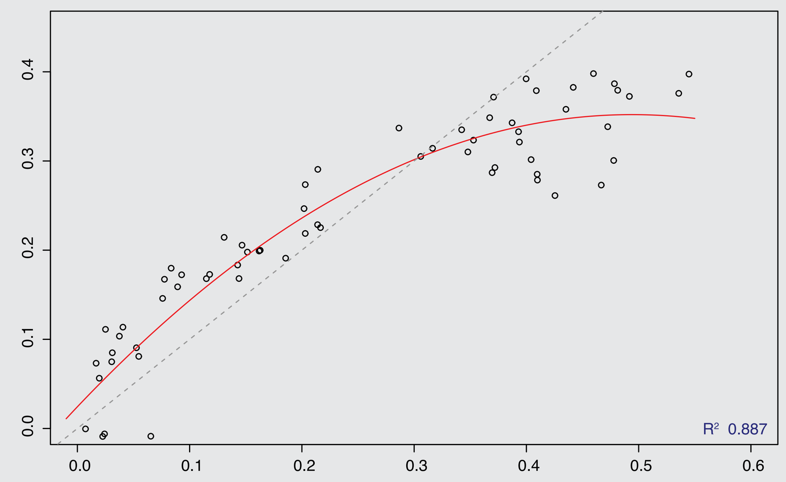

Figure 7 Red-edge vegetation indices for the Fig. 6 site. x: true NDVI; y: red-rejection NDVI, (NIR-B)/(NIR+B). Red: 2nd order polynomial fit; grey dashed: 1 to 1 line. A similar relationship was found for y: excess greenness (not shown).

The red-edge index (c) shows an advantage over the green-band index (d): the pattern of crop development is better captured, thanks to the closer relationship of NDVI to chlorophyll absorption. NDVI can be calculated using the blue band (which requires one flight instead of two), but this increases the saturation effect at the high value range (Fig. 7).

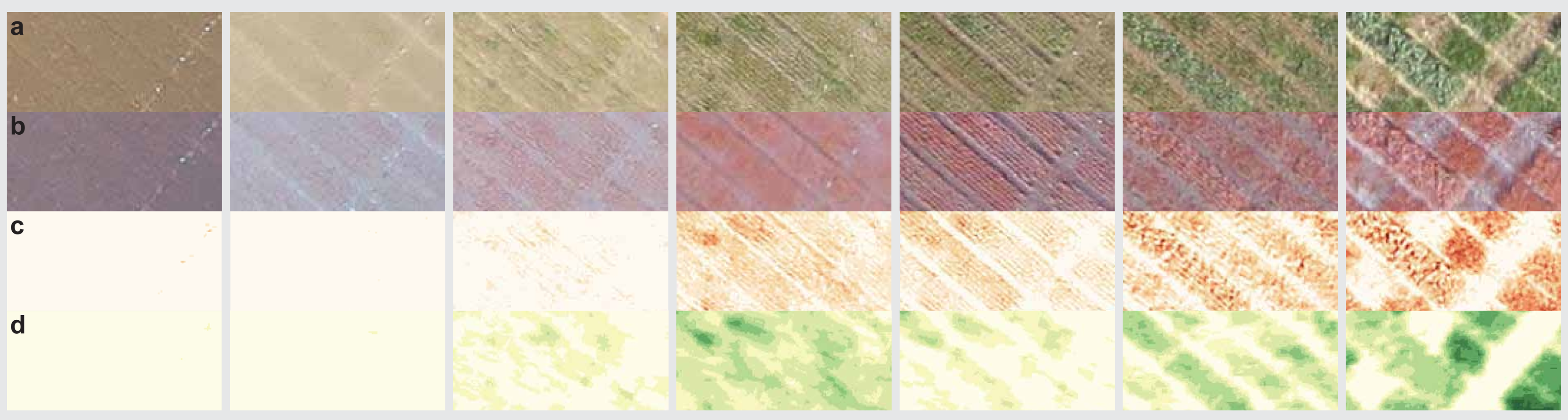

Figure 6 Series of images aquired using the two filter setups (**a**: true color; **b**: false-color IR) for an agricultural research facility [6]. Two radiance-based indices are **c**: true NDVI (range 0-0.5) and **d**: excess greenness (range 10-90). The area is 8x4 m. Dates (2013): May 28th (freshly sown), June 6th, June 18th, June 26th, July 1st, July 26th and Aug 15th.

Conclusion

CGCs can be effectively modified for NIR sensitivity, but to achieve spectrally meaningful measurements and indices, the raw images need to be flat-field corrected and radiometrically calibrated before mosaicking. The calibration curve is not necessarily linear, for which empirical line correction may be inaccurate. CGCs have limited options for reflectance calibration, which gives spectral indices preference over single-band metrics. Red-edge indices are closest related to chlorophyll absorption and vegetation development, but can, because of CFA constraints, not be retrieved from a single acquisition. Blue substitution (e.g. red-rejection NDVI) remediates this, but increases the saturation effect at high index values.

References and notes

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** mosaic of 181 true-color CGC images around the Eschikon research site [6]. Spatial resolution ca. 5cm, area ca. 1x1km. Date: May 28th 2013.

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