On the accuracy of infrared-converted drone cameras for use in vegetation and environmental monitoring

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Abstract

Drones equipped with cameras sensitive to near-infrared wavelengths are increasingly being used in environmental assessment studies and in agriculture. These cameras can measure vegetation cover, extent of eutrophication in water bodies, and aspects of crops, such as growth vigour, biomass and potential yield. Infrared converted cameras that capture near-infrared wavelengths offer a low-cost alternative to multi-sensor multispectral cameras or drone-borne spectrometers. However, some studies point to lower accuracy in measurements by such infrared converted sensors. So, to what extent can infrared converted cameras be used to quantify vegetation condition? This study compared vegetation index measurements (NDVI) from an infrared converted camera to measurements by a multispectral camera and a handheld NDVI meter, captured over soybean and potato fields. It was observed that infrared converted camera derived NDVI was consistently lower over crop than multispectral and handheld based measurements. However, correlation between the sensor values were high ($r = 0.95, r = 0.87$ for respective survey days). This suggests that the infrared converted sensor is valuable for qualitative assessment of vegetation status across a farm. Based on the result of this study we however recommend caution when using infrared converted camera for quantitative applications like calculating fertiliser prescription rates from vegetation index maps. We discuss possible reasons for the lower vegetation index measurements observed, noting overestimation of reflectance in the red band, but underestimation in the near-infrared band, leading to low NDVI values.

1. Introduction

Drones equipped with cameras are increasingly being used in environmental assessment studies and agriculture. For example, such drone-camera systems have recently been used to monitor ocean algal blooms (Fernandez-Figueroa, Wilson, and Rogers 2022) and wetland inundation and vegetation change in an estuarine reserve (Dehm, Becker, and Godre, n.d.). Drone cameras are also used to measure different aspects of crops, such as growth vigour, biomass and water-stress (Hafeez et al. 2022). Specialized cameras for vegetation monitoring often have a sensor sensitive to wavelengths in the near-infrared part of the EM-spectrum. Healthy photosynthesising vegetation shows high reflectance in near-infrared wavelengths, but comparatively low reflectance in the red part of the spectrum (Myneni et al. 1995). So, if red and near-infrared wavelengths are recorder by a drone sensor, the condition or growth vigour of vegetation can be quantified with vegetation indices such as the Normalised Difference Vegetation Index, or NDVI (Huang et al. 2021). This index ranges from $-1$ to $1$, with higher values interpreted as vegetation with higher growth vigour. Vegetation indices like NDVI are being applied to measure eutrophication in waterbodies (Barajas et al. 2021; Sheng, Azhari, and Ibrahim 2021), and to quantify the condition of crops, and how it varies spatially and over time. Such drone-camera systems offer a comparatively low-cost method to capture image data for wide areas, and allows data to be spatially referenced so that it can be overlaid with other sources of spatially explicit data. Different drone camera sensors however have different price-points and characteristics that may influence the quality of measurements (Nijland et al. 2014). Thus, as the use of these technologies scale in agriculture and environmental studies, it is all the more necessary to evaluate the measurement bias or limitations of different drone sensor types.

There are different ways in which cameras are designed to capture near-infrared wavelengths (Maes and Steppe 2019). One option is that the camera has a separate imaging sensor and lens for each wavelength band. The second option is that a single sensor red-green-blue (RGB) camera is modified to become also sensitive to light in the near-infrared spectrum (Lebourgeois et al. 2008). In this article these are referred to as infrared converted cameras (Nijland et al. 2014), although they are also referred to as modified RGB (Lebourgeois et al. 2008; Wang and Brinker 2020) or modified multispectral cameras (Fernandez-Figueroa, Wilson, and Rogers 2022). Infrared converted cameras work by removing the filter which blocks NIR light from entering the sensor, and then substituting one of the RGB camera's bands for the NIR band. For example, instead of Red-Green-Blue, the camera becomes sensitive to Red-Green-NIR. The single sensor infrared converted cameras are cheaper (by order of magnitude) than multispectral cameras with multiple sensors. They thus pose an attractive alternative, especially in cases where ‘proper’ multispectral cameras are considered prohibitively expensive. Several studies highlight the value of lowering the cost of technologies that can support environmental monitoring (Fernandez-Figueroa, Wilson, and Rogers 2022) and agriculture (Fernandez-Gallego et al. 2019; Cucho-Padin et al. 2020; Corti et al. 2019).

Infrared converted cameras are an appealing option for drone agriculture remote sensing because of their comparative low-cost and ability to capture near-infrared wavelengths. but it is necessary to verify the accuracy of spectral measurements made by these
sensors. Despite being successfully used in studies (Lebourgeois et al. 2008; Argolo dos Santos et al. 2020), some authors reported lower measurement accuracy for infrared converted cameras, if compared to multi-sensor cameras or spectroscopes (Bueren et al. 2015; Gomes et al. 2021; Nijland et al. 2014). This might partially be because the bands captured by single-sensor RGB camera is usually sensitive to light outside of the target wavelengths, and so measurements in specific band may be polluted by light in other parts of the spectrum (Burggraaff et al. 2019; Berra et al. 2015). This means for example that a modified RGB camera may report incorrect values for a specific band, because the sensor is also capturing light from the neighbouring bands.

Before such cameras can be recommended for operational use on farms, it is important to verify that spectral measurements and vegetation indices derived from the infrared converted camera correspond well to measurements made by other ‘proper’ multispectral cameras, or hand-held spectrometers. The study by Gomes et al. (2021) investigated this dynamic for the Mapir Survey3W commercial infrared converted camera, by comparing it to the multispectral MicaSense RedEdge-MX camera. The study calculated the vegetation index NDVI of a coffee plantation using both cameras, as well as a handheld NDVI sensor. It was observed that NDVI measurements made by the infrared converted camera were consistently lower, if compared to the multispectral camera and handheld NDVI sensor. This finding may have important repercussions for the operational use of such infrared converted cameras, since farmers or agriculture service provider companies may incorporate erroneous readings from the infrared converted camera into their crop monitoring system. This can lead to incorrect interpretation of crop condition, or wrong application of fertiliser, in a case where a variable rate application system is used. Or, in a eutrophication study, the extent of algal blooms may be underestimated, for example.

The current study reinvestigates the question of the suitability of current commercial infrared converted cameras for use in vegetation condition monitoring. To improve continuity between research, we present a case-study that considers the same multispectral camera, handheld NDVI sensor and infrared converted camera used by the study of (Gomes et al. 2021). Our experiment differs however in the calibration technique used, specific spectral filter used in the infrared converted camera, and also the crop type that was captured. By critically evaluating the performance of infrared converted sensors for crop monitoring, the agriculture sector can make informed decisions about what systems to use, and their potential challenges (Bueren et al. 2015).

2. Methodology

2.1 Study site

Field surveys were conducted on a commercial crop farm outside Iwamizawa City in Hokkaido prefecture, Japan. Surveys were flown over a potato field (33,984 m$^2$) and a soybean field (18,898 m$^2$) Fig. 1. This study site was chosen, because of the willingness of the farmer to allow drone and field surveys on his fields, and secondly because the farm was near enough from the university to allow multiple field surveys. Hokkaido prefecture is an agriculturally important prefecture in Japan, accounting for 25% of Japan's total cultivated area. Farming in this prefecture also consists mostly of commercial farming households, characterised by large farms (13 times larger area per household than other prefectures) that are managed on a full time basis (Hokkaido DoA 2020). These characteristics make Hokkaido's agriculture sector more suitable for the adoption of new agricultural technologies like drones (Swinton and Lowenberg-Deboer 2001). Hokkaido is also the largest producer of potatoes (32.8% share) and soybean (47.7%) among prefectures in Japan (Hokkaido DoA 2020). Two field surveys were conducted, the first one 5 July 2022, when the soy plants were still small, and potato crop was in the vegetative growth stage. The second survey was done on 17 August 2022, approximately 6 weeks after the first. At this time the potato crops had started senescence, and the soy crop was showing strong vegetative growth.

2.2 Field surveys

On the two survey days drone surveys were conducted by 2 drone-camera systems. A summary of the field-survey details are given in Table 1. The Micasense RedEdge-MX camera (Micasense, Inc. 2019) was mounted on a DJI Inspire 2 quadcopter drone. The infrared converted camera used in the study was the Mapir Survey 3W camera with OCN filter. OCN captures 3 bands: orange, cyan, and near-infrared (Mapir, n.d.b), however, the manufacturer recommends the orange band to be treated as red in equations for deriving vegetation indices. The Mapir sensor was flown on a DJI Phantom 4 Pro drone. The Inspire 2 surveys were flown at 40 m
Above Ground Level (AGL), and the Phantom 4 flights were done at 50 m AGL. We selected a 50 m target flying height for the Mapir camera to correspond to the studies by Gomes et al. (2021) and Argolo dos Santos et al. (2020). However, because the MicaSense sensor has a lower image resolution we flew the MicaSense sensor at the lower target height of 40 m. This height was chosen so that ground sampling distance differed less than 5 mm/px between the two sensors. Both camera manufacturers supply tools for calculating sensor ground sampling distance at specified heights. Autonomous flight plans were set using 75% overlap between images. The surveys were conducted between approximately 13:00 and 14:30 local time.

Table 1: Summary of Drone-camera systems used during field surveys.

<table>
<thead>
<tr>
<th>Property</th>
<th>MicaSense RedEdge-MX</th>
<th>Mapir Survey3W OCN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectral bands (band centre, )</td>
<td>blue (475) + green (560) + red (668)+ NIR (842) + red edge (717)</td>
<td>Orange (615) + Cyan (490) + NIR (808)</td>
</tr>
<tr>
<td>Drone platform used</td>
<td>DJI Inspire 2</td>
<td>DJI Phantom 4 Pro</td>
</tr>
<tr>
<td>Flight height (AGL)</td>
<td>40 m</td>
<td>50 m</td>
</tr>
<tr>
<td>Image overlap</td>
<td>75 (%)</td>
<td>75 (%)</td>
</tr>
<tr>
<td>Survey local time</td>
<td>13:00 - 14:30</td>
<td>13:00 - 14:30</td>
</tr>
</tbody>
</table>

Both the camera manufacturers supply ground calibration panels that are used for image calibration during subsequent processing. The respective ground panels were photographed before take-off Figure 2.

To compare the drone survey results, we measured NDVI values at sample locations in the two fields using the handheld Trimble Greenseeker NDVI meter (Trimble Inc. 2022). The Trimble Greenseeker uses an active sensor that emits bursts of near-infrared (780 nm) and red (660 nm) light, and then measures the reflectance back to the sensor. The device then calculates an NDVI reading and shows it on an LCD screen. It has a 25 cm field of view when capturing at a height of 60 cm. To correspond field sample measurements with drone based measurements we placed A4 papers and plastic markers in the field at the sample locations. These markers were visible from the drone images, and could be used to identify the locations to sample NDVI from drone images. Since measurements of NDVI are assumed not to be affected by the type of crop or surface measured, we considered sample locations from the ground, potato field and soybean field together. On the first survey, 12 samples were taken with the Trimble Greenseeker, and on the second day, 26, totalling 38 samples.

2.3 Data calibration and processing

The images captured by the two cameras were calibrated to reflectance images, to be used in derivation of the NDVI vegetation index. Mapir supplies official GUI software for radiometric calibration of Mapir camera images, called Mapir Camera Control (MCC), as well as python based processing scripts (Mapir, n.d.a). We used the software to convert RAW images to tiff, apply vignette corrections and convert images values to reflectance. For calibration to reflectance the software used the calibration panel images taken during the field survey Fig. 2. The resulting calibrated images were processed into a single georectified orthomosaic using the Windows command line utility for OpenDroneMap (OpenDroneMap Authors 2020), an opensource drone image processing software. For the MicaSense RedEdge-MX camera, the OpenDroneMap software was used to apply radiometric calibration to reflectance, since the software has built in support for this camera model. The software applies black level, vignetting and row gradient gain/exposure compensation (OpenDroneMap Authors 2020). In the software the option was selected to compensate for spectral radiance measured by a down-welling light sensor. The output of this processing was a GeoTIFF orthomosaic with a layer for each of the 5 spectral bands captured by the RedEdge-MX camera. However, for some areas in the field the resulting orthomosaic was blurred, and had lower resolution then the rest of the image. To account for this, we selected individual images of the sample locations that were in the blurred part of the orthomosaic. These individual images were also radiometrically calibrated, and then georectified to overlap with the orthomosaic. To radiometrically calibrate the individual RedEdge-MX images, we used the python based image processing utility provided by MicaSense (Micasense, Inc. 2022), instead of the OpenDroneMap utility, since it is not suitable for processing only individual images.
Next, the NDVI index was calculated from the reflectance images using Eq. 1 given below, where NIR is reflectance in the near-infrared band, and Red is reflectance in the red band. For the two cameras considered, the specific red and near-infrared bands can be seen in Table 1.

\[
NDVI = \frac{NIR - Red}{NIR + Red} \tag{1}
\]

We used the sample location markers visible in the orthophoto to create vector point file of the sample locations. A buffer of 10 cm radius was made around each sample point location, and then average NDVI value in the buffer was extracted from the NDVI maps. We used the buffer, since the handheld sensor captures NDVI from about 40–50 cm above the plant canopy, and thus captures NDVI for an area. The exact field of view, and thus ground sampling distance of the GreenSeeker sensor was however not known, causing ambiguity about the precise area/plants measured by the sensor. Also, for three sample points in the soybean field, the markers were not visible, so we selected NDVI in the first part of the row that the marker was noted down to be in.

2.4 Data Analysis

Three analyses were considered for the acquired data.

Firstly, the NDVI values measured by the three sensors were plotted for each sample location, to show the relationship between the values. Next to quantify the relationship, we fit a least-squares Linear model between the drone based measurements, and the handheld sensor based measurement. If the sensors measured accurately there should be an approximately (1–1) relationship between NDVI measurements of the three sensors. The slope of the model is an indication of difference in the sensor's sensitivity to NDVI changes — a slope of 1 means NDVI values of the sensors scale the same. The intercept is taken to be an indication of a systematic under or over estimation of NDVI. The model \( R^2 \) is an indication of whether the assumption of a linear relationship between the sensors’ NDVI values was suitable.

For a second analysis, we generated 5000 random points in the study area, and extracted NDVI from a 10 cm buffer around the point. This was to extend the first analysis by showing a clearer relationship between NDVI values captured by the multispectral and infrared converted cameras. The correlation between the values from two sensors are calculated, and the points are plotted.

For the third analysis, we generated histograms of the reflectance from the red and near infra-red bands of individual images over the same portion of crops in the field, to understand how the difference in NDVI may be caused by differences in the reflectance measurements in the different bands.

3. Results

3.1 NDVI at field sample points.

We measured NDVI with the three described sensors on two survey days in potato and soybean fields, adding up to 38 sample points. Figure 4 shows the NDVI values measured by each sensor for the two survey days. The figure shows that the infrared converted sensor reported lower NDVI, compared to the multispectral camera and Trimble Greenseeker handheld NDVI sensor. On both days the multispectral drone camera reported higher NDVI values than the handheld sensor. The specific relationship between the sensor readings was evaluated with a least-squares linear model. The multispectral camera’s NDVI readings scaled almost 1–1 with the handheld sensor (model slope = 0.77, Table 2), but the camera’s readings were higher (model intercept = 0.28, Table 2). The linear model fit between the handheld and MicaSense sensor was better than the fit between the handheld and Mapir infrared converted sensor \( R^2 = 0.88 \) and \( R^2 = 0.4 \) respectively, Table 2.

Table 2: Linear Model coefficients for model between drone sensor NDVI and handheld NDVI reading.
<table>
<thead>
<tr>
<th>sensor</th>
<th>term</th>
<th>estimate</th>
<th>p.value</th>
<th>R2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapir Survey 3W</td>
<td>intercept</td>
<td>-0.0541</td>
<td>0.0043</td>
<td>0.3988</td>
</tr>
<tr>
<td>Mapir Survey 3W</td>
<td>slope</td>
<td>0.1388</td>
<td>0.0000</td>
<td>0.3988</td>
</tr>
<tr>
<td>MicaSense RedEdge-MX</td>
<td>intercept</td>
<td>0.2767</td>
<td>0.0000</td>
<td>0.8830</td>
</tr>
<tr>
<td>MicaSense RedEdge-MX</td>
<td>slope</td>
<td>0.7693</td>
<td>0.0000</td>
<td>0.8830</td>
</tr>
</tbody>
</table>

In Figure 5 the black diagonal line represents the 1-1 line between drone-based measurements and the handheld sensor’s NDVI measurements for all sample points. The low NDVI measured by the infrared converted camera can be seen by the red line lying below the diagonal line, with a shallow slope (slope = 0.14, Table 2). The multispectral sensor (line in blue) measured NDVI closer to the 1-1 line, but consistently measured higher NDVI than the handheld sensor.

3.2 Comparison of NDVI across field

Considering NDVI extracted from 5000 random point locations in the field, the relationship between NDVI measured by the multispectral and infrared converted camera is similar to the case were the field sampled locations were used (Fig. 4). For both study dates the NDVI values by infrared converted camera were lower than the values measured by the multispectral sensor (Fig. 6), and the range of values is also lower, suggesting that the infrared converted camera is less sensitive to variation in the plant condition, as quantified by NDVI index. Despite the difference in the scale of the values, there is still however high correlation between the two camera sensors’ NDVI readings (survey 1: \( r = 0.95 \); survey 2: \( r = 0.87 \)).

3.3 Individual band reflectances

To investigate the cause of the difference in measured NDVI, we consider the reflectance in red and near-infrared bands for a scene in the potato field. For the NIR-band the MicaSense RedEdge-MX measures much higher reflectance over vegetation than the Mapir Survey3W camera (Fig. 7). However, the RedEdge-MX camera measured lower reflectance in the red-channel than the Survey3W. If the MicaSense sensor’s readings are considered accurate, it thus suggests that the infrared converted sensor captures more noise, since it overestimates red in a scene where red values are actually low, and underestimates NIR. Based on the formula for NDVI (Eq. 1), overestimating red and underestimating near-infrared will lead to underestimates for NDVI, as observed (Fig. 4). For ground pixels the NIR and red reflectance measurements are however similar between the sensors.

4. Discussion

In this case study it was observed that the Mapir Survey3W OCN camera — a commercial infrared converted camera marketed for use in agriculture — consistently measured lower NDVI values in a crop field, compared to a more expensive multi-sensor multispectral camera, and a handheld NDVI meter. This result reflects those of the study by Gomes et al. (2021), who also observed lower NDVI measurements from Mapir Survey 3W camera, compared to multi-sensor and Greenseeker handheld sensor, and also (Argolo dos Santos et al. 2020) who noted Mapir Survey RGNIR measured lower NDVI in a maize field than reported by other studies. A possible explanation for this observation may be that the camera considered in our study overestimated reflectance in the red-channel (Fig. 7). The Survey 3W OCN uses an orange band in the place of red, thus having a central wavelength nearer to green wavelengths than common for red bands. This fact, together with the broad band-sensitivities of single-sensor RGB cameras (Burggraaff et al. 2019; Berra et al. 2015) might cause the orange band to capture too much light from the green part of the
spectrum (Fig. 8). Since vegetation also reflects green light, the orange channel might be measuring too high reflectance over vegetation leading to underestimation of NDVI measurements (Fig. 4). If this is the case, it will be better to use infrared converted cameras with red band centred further away from the green wavelengths. Yet, the camera manufacturer supplied wavelength sensitivity chart shows no overlap in the sensitivities of the Survey 3W OCN camera’s orange band with green wavelengths (Mapir, n.d.b). A possible alternative explanation is that the incorrect measurements are caused by a problem in the calibration of images to reflectance. This could happen if the lighting on the calibration target during its capture did not represent the lighting over the field during the flight because of shadow or cloud. However, the fact that similar results were observed on separate field survey days, and also by Gomes et al. (2021), who used a different calibration approach, suggests that calibration errors are not the sole cause of the error in the NDVI reading. And also, the fact that over the same scene of crops, the Mapir camera had lower near-infrared, but higher red reflectance than the multispectral MicaSense camera (Fig. 7), further suggests that the errors are caused by the sensor, rather than the calibration. The study by Nijland et al. (2014) investigated the utility of infrared converted cameras for vegetation monitoring, but they also found inadequate band separation to reduce the accuracy of reflectance measured by these cameras. If inadequate band separation is to blame for inaccurate readings, a camera modified to exclusively measure a vegetation index like NDVI might improve results by using an additional filter that blocks green light, and so reduces contamination into the red and near-infrared bands. Also, filters that are sensitive to red light further away from the green bands (longer wavelengths) may help to reduce noise, compared to the Orange (615 nm) filter used in our study.

Bueren et al. (2015) suggest that vegetation indices from RGB and infrared converted cameras are most suitable for simple (qualitative) assessment of vegetation condition over a large area. In our study we noted high correlation between VI measurements made between the multispectral and infrared converted sensor (r = 0.96 and r = 0.87 for the two survey days respectively), similar to Gomes et al. (2021) and Bueren et al. (2015). This indicates that most of the variation in crop condition that is measured by the multispectral sensor is also captured in the lower-cost infrared converted camera. So, the infrared converted camera may successfully be used to qualitatively assess the variation in vegetation status across the study area. Such qualitative monitoring might help farm managers to easily identify specific problem areas that can then be further investigated in-field. However, the results of this study suggest that the infrared converted camera considered might not be suitable to inform quantitative decisions like fertiliser application rate in Variable Rate Application systems (Alley et al. 2011) or biomass/yield estimation models that are calibrated for accurate NDVI measurements.

If infrared converted cameras are indeed mostly suitable for qualitative type measurement, it brings to question whether such converted cameras hold an advantage over unmodified RGB cameras that are generally even cheaper than infrared converted cameras. Regular RGB cameras attached to drones have indeed successfully been used for biomass and yield estimation studies (Li et al. 2018; Argolo dos Santos et al. 2020; Bendig et al. 2014), and for estimating biomass of green algae in the ocean (Xu et al. 2018). Some of these studies utilized the fact that RGB cameras capture comparatively high resolution images, which are used to generate three dimensional models of vegetation canopy. This 3-D information, together with visible-band vegetation indices may be sufficient for calculating crop biomass, which in turn can be related to expected yield in some crops, or area covered by eutrophication in water bodies. These visible band indices might not be as sensitive to variation in growth vigour as indices capturing near-infrared (e.g., NDVI), but they are suitable for distinguishing crops from background (Riehle, Reiser, and Griepentrog 2020), and thus for estimating the area of crop cover or biomass related parameters. Also, because of the shortcomings of single-sensor cameras to accurately capture near-infrared wavelengths, vegetation monitoring using just regular RGB cameras, coupled with visible band indices, might be better than infrared converted cameras. Nijland et al. (2014) observed that an unmodified RGB camera could quantify crop conditions more accurately than the infrared converted camera, despite the theoretical advantage of the converted camera to capture infrared wavelengths. Fernandez-Figueroa, Wilson, and Rogers (2022) also tested an infrared converted Mapir Survey 3W for measuring Chl a concentration in ocean algal blooms, and found that the converted camera's vegetation indices correlated worse to measured Chl a than visible band indices captured by a regular RGB camera.

5. Conclusion

In conclusion then, our study observed that NDVI measured by a infrared converted did not agree well with a more expensive (multi-sensor) multispectral camera, and so should be used cautiously for quantitative applications like determining fertilizer application rates in crop fields. The inaccuracy might be caused by too broad band sensitivities, leading to the red channel capturing light from the green wavelengths. This problem might further be exacerbated by the orange (615 nm) filter used for the red channel in the
Survey 3W OCN camera, which is itself nearer to green wavelengths than most other infrared converted or multispectral drone cameras. However, since the infrared converted camera's NDVI values still correlated well with measurements or multispectral sensor, it can be useful for qualitative assessment of comparative vegetation condition to easily identify problem areas. However, for such applications unmodified RGB cameras with visible band indices might be equally suitable. Finally, low-cost RGB or modified cameras might still be suitable for some quantitative applications like biomass estimation, if care is taken to use methods tailored to the advantages and limitations of these sensors.

Declarations

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Authors contributions: All authors contributed to the study conception and design. Stephan Louw, Chen Xinyu and Ram Avtar designed the study and conducted a formal analysis. Stephan Louw, Chen Xinyu and Ram Avtar conducted the field work. Stephan Louw processed data and interpreted the results. Ram Avtar is the mentor for the study and obtained the funding. All authors discussed the results and contributed to the writing and review of the final manuscript.

Data Availability: Data is available based on the request to the corresponding author

Ethical approval: The research does not involve any human participants and/or animals.

Consent to participate: Not applicable.

Consent to publish Not applicable.

Competing Interests: The authors declare no competing interests.

References


**Figures**

![Figure 1](image-url)
Field Study Site: potato and soybean fields, Iwamizawa City, Japan, July 2022.

Figure 2

Photos of calibration panels for the MicaSense (A) and Mapir (B) cameras, taken before flight.

Figure 3

Example of sample location marker (inside red square), as seen from Mapir camera flown on drone 50m AGL
Figure 4

NDVI values measured by the three sensors (indicated by point colour) at the sample locations for the first (a) and second (b) field survey days.
Figure 5

Relationship between NDVI measured by hand-held sensor (x-axis) and the two drone sensors (y-axis) at the 38 sample points measured over the 2 field surveys.
Figure 6

NDVI values measured at 5000 random points in the study-area, compared between the multispectral (x-axis) and infrared converted (y-axis) cameras. Fitted line is a least-squares linear model. (a) is for the first survey (2022/07/05) and (b) for the second survey (2022/08/17).
Figure 7

Density plots of reflectance in the near-infrared and red channels, as captured by the infrared converted and multispectral sensors. Result shown separately for crop covered and ground areas in the field.
Figure 8

The difference in red reflectance captured by the infrared converted and multispectral camera. Shown for a scene over the potato field, with (a) RGB image, (b) the difference between Mapir and MicaSense red channels, (c) Mapir red reflectance, and (d) MicaSense red reflectance.