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SPECTRAL ANALYSIS OF IMAGES OF PLANTS UNDER STRESS USING A CLOSE-RANGE CAMERA

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ABSTRACT:

Plants signal their health in a broader spectrum than we can see with our eyes. We compared sunlight reflectance on plants at spectral wavelengths ranging from 430 nm to 870 nm in our study. These are based on multispectral images captured at a distance of 2m. Indoor plants were observed over a period of 18 days and stressed due to a lack of sunlight or water. Wild sedge photographed on the forest floor at close range and with a difficult capture setup produced results comparable to published multispectral signatures derived from aerial imagery. Changes of leaf reflectance were noticed in spectral signatures and in vegetation indices. When calculating vegetation indices, our results show that comparing red and red edge reflectance values is superior to comparing red and NIR reflectance values.

1. INTRODUCTION

Plants signal their health in a broader spectrum than we can see with our eyes. This has been proven many times with Multispectral Imagery (MSI). As advertised on the Copernicus Global Land service website, MSI is used for monitoring vegetation quality, quantity and more. The greenness of vegetation can be emphasised using the Normalised Difference Vegetation Index (NDVI) including the bands red and near-infrared (NIR). This indicates the potential of plants performing photosynthesis. Exchanging the red channel with red edge forms the Red Edge Chlorophyll vegetation Index (RECl) or Normalised Difference Red Edge index (NDRE).

$$NDVI = \frac{NIR - red}{NIR + red} \qquad NDRE = \frac{NIR - rededge}{NIR + rededge}$$

Red edge is more sensitive reflecting the light on the cellular structure of a plant than the red channel. Normalised Difference Water Index (NDWI) uses the green and NIR channel and indicates wet and dry land areas (EOS Data Analytics, Inc., 2023). These monitoring indices are important for optimising water and fertiliser distribution in agriculture. In forests, they can be used to monitor plant health and growth over time, indicating which plant types have more difficulties coping with weather extremes.

Multispectral information can also be collected with multiple laser beams. With multispectral Light Detection and Ranging (LiDAR), the equivalent water thickness can be detected in plants using laser beams with wavelengths of 690, 905, and 1550 nm (Junttila et al., 2018). Segmentation between plants and other objects was also improved (Chen et al., 2020). The multispectral LiDAR approach shows to enhance digital terrain model generation, because different uncertainties depending on vegetation or buildings could be included (Ali et al., 2021). Furthermore, with multiple LiDARs the carbon storage in urban trees can be estimated (Chen et al., 2018). Here, the laser beams were the base of NDVI and NDWI, which is commonly extracted from imagery, and was calculated with laser beams red, green and NIR. The same work showed that detecting tree tops, which is frequent in the tree segmentation task, improved with this approach. Hakula et al. (2023) could increase the tree species classification accuracy from 73% to 91% with the use of multispectral LiDAR. The classification of healthy, dead and attacked trees achieved better results when using multispectral Unmanned Aerial Vehicle (UAV) imagery instead of only RGB data (Junttila et al., 2022). Plant stress can be detected using red edge, for example in grass, bean and wheat, stressed due to high natural gas concentrations in the ground (Smith et al., 2004).

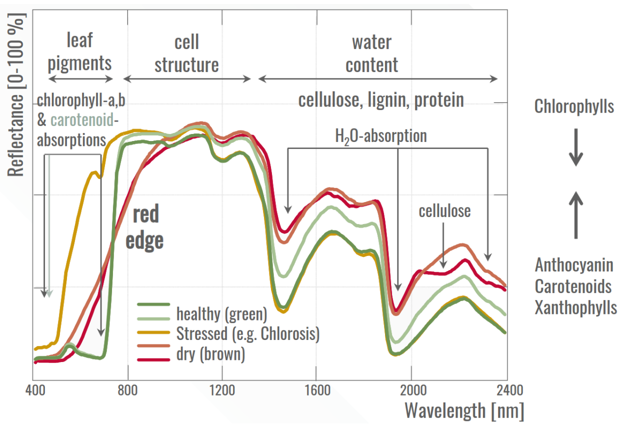

Figure 1. Spectral signatures of healthy, stressed and dry plants. Figure adapted from Brosinsky et al. (2019), SAR-EDU material published under CC BY-SA 4.0.

Surveying plants at various spectral wavelengths reveals more about the health of the plant than is visible to the naked eye. From around 400 to 700 nm, which includes blue, green and red colour, the light reflectance indicates the amount of chlorophyll, carotenoid and other pigments in the plant (Figure 1). At around 700 nm the reflectance rises drastically has a plateau

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until around 1300 nm. From the beginning of this plateau until 2500 nm, the region indicates cell structure, and the amount of water in a plant and its leaves, including protein, lignin and cellulose levels(Kokaly et al., 2003). Plants absorb light to generate power, especially in the visible spectrum, while rejecting other spectral wavelengths such as near-infrared. If plants are stationed in a rather shadow place, they will tend to darker shades of green, meaning they absorb more light. In contrast, if plants receive more light than needed, they will tend to a lighter shade of green and rejecting more light, to not overwhelm their system. Although leaves' greenish colour is noticeable to the human eye, it has little impact on the energy balance of whole leaves (Kume, 2017).

The aim of this study is to determine whether the MicaSense RedEdge MX Dual camera system in a close-range setup supports previous related work. This camera system is composed of 10 separate lenses, one for each band. We compare the reflectance of sunlight on plants at spectral wavelengths ranging from 430 nm to 870 nm. Indoor plants were monitored over period of 18 days and put under stress due to a lack of sunlight or water. The multispectral signature of a wild sedge growing on the forest floor was compared to a previously published multispectral signature. In addition, we discuss the effectiveness of the well-known NDVI as well as our experiences with the MicaSense dual camera system for close range applications.

2. METHODS

To compare pixel values on different objects, the same pixel has to be observed in each band. In the case where each band is captured by a different lens, each image stack of ten channels has to be merged into a single image. This was accomplished using opencv's motion homography function, which is an iterative approach to finding the same object in multiple images. The output includes a transformation matrix, which presents the image rectification and registration per band. The overlapping images are clipped to a common border. Following that, each 10-channel image is viewed and a patch is manually selected. This patch includes a centre pixel and a number of pixels in each direction. For example, a buffer of 10 pixels results in a 20x20 pixel patch. The patches include only one object type, such as only one leaf. For each patch the mean intensity is calculated for each band. References values were taken from the MS reflector panel provided by MicaSense, where about 50% of light is reflected. The exact reflectance percentages was obtained from MicaSesnse. The mean values per patch are calibrated with the reference values per band with the following equation, adapted from MicaSense.

$$value = \frac{refl_{obj} \times (1 - refl_{ref\%})}{refl_{ref}}$$

With $refl_{obj}$ being the mean reflectance of the object per patch and band, $refl_{ref\%}$ the exact percentage which is reflected on the reference panel, and finally $refl_{ref}$ is the mean light reflectance value per band on the reference panel.

Plants were captured thrice and for each image, three patches covered the same object type. Thus, an average value per day was taken from 9 patches. Results are plotted as a graph showing the change of reflectance for each object over the 10 bands, named signature.

3. EXPERIMENTS

In this study, we use the MicaSence RedEdge MX Dual System, which was also utilised by Dersch et al. (2023) with a flight altitude of 80-90 m. It has comparable spectral bands to common satellite imagery such as Landsat 8, Sentinel 2, Wordview-3 and Planetscope (Figure 2). Two separate cameras, each with five bands, make up the camera system, along with a Downwelling Light Sensor (DSL2). When ambient light conditions change in the middle of a data collection, for example in forests under the canopy, DSL2 is used to improve reflectance calibration. The cameras are simultaneously triggered once every second, and each band is saved as a 16-bit TIFF file with a resolution of 1280 by 960 pixels. For communicating with a computer, Ethernet or WiFi can be chosen. The computer starts and stops the continuous capture and serves as a control station for the cameras. The 10 individual lenses each have a 47.2° horizontal field of view and a global shutter that syncs with all other lenses. Despite there being two cameras, we will refer to the set as one camera for simplicity. The camera bands include the following electromagnetic wavelengths (band span): coastal blue 444 (28), blue 475 (32), green 531 (14), green 560 (27), red 650 (16), red 668 (14), red edge 705 (10), red edge 717 (12), red edge 740 (18) and NIR 842 (57).

The camera matrix K is a follows, shown for the blue channel:

$$K = \begin{bmatrix} 1451.7 & 0.0 & 632.5 \\ 0.0 & 1451.8 & 488.3 \\ 0.0 & 0.0 & 1.0 \end{bmatrix}$$

The distortion coefficients are divided in tangential distortion $p_1 = -0.105$ and $p_2 = 0.194$, and radial distortion $k_1 = 0.001$, $k_2 = -0.000$ and $k_3 = -0.126$.

Images were taken in August 2023 in Darmstadt, Germany. The vegetation includes house and forest plants (Table 1). House plants are indoors in standard households. The plants stayed at room temperature and were photographed outside in the shadow at 2 m distance, from the same spot each time. During the time series, we placed the plants in the same direction and position between days. Forest plants grow uncultivated and were photographed there and not in full sun. All plants prefer rather mesic moisture, meaning moderate moisture supply (Wisconsin Department of Natural Resources, 2022), and a variance of full sun to full shadow.

Three experiments were run to demonstrate various plant stress scenarios and capture setups. The first experiment includes a stress test of indoor plants. For this, four young Dracaena reflexa var. angustifolia (short: dracaena) were observed and put under stress. All four were cut on the same day from the mother plant, put in a glass of water for 2 weeks and then planted in a different pot each. At the beginning of the experiment, all four plants had full set of roots reaching the bottom of the pot. Plant 1 was treated with the average amount of sun and water, plant 2 was given the same amount of sun but no water. Plant 3 and 4 were given the same amount of water as plant 1 but given no light. These two plants were put in a dark cabinet and only received light during the few minutes of capturing the images. In this testing period images were taken everyday at 4 pm. The patches had a size of 6×6 pixel.

The second experiment compared 4 spider plants that received different amount of sunlight over 4 months. Plant 1 and 2

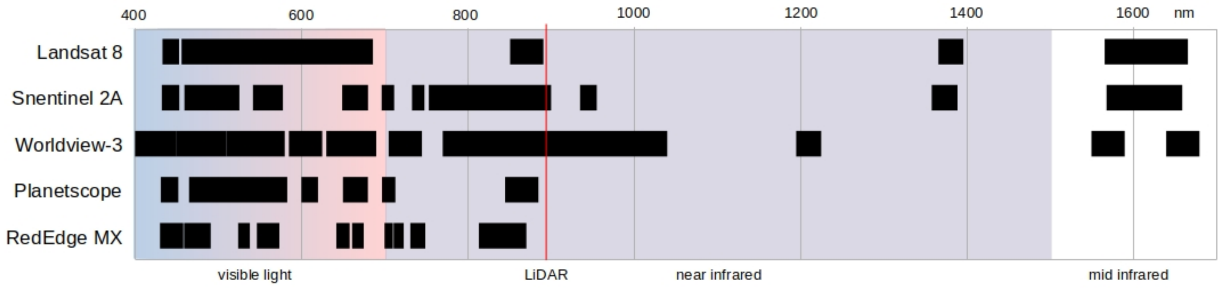

Figure 2. Comparison of spectral bands between satellites and the RedEdge MX Dual Camera used in this work. Overlapping bands within the same sensor were fused into one bar. LiDAR refers to Velodyne VLP16 Puck Lite at 903 nm. Wavelengths in nm.

Latin Name	English Name	Plant Habit	Sun Requirements	Water Preferences	Source
Dracaena reflexa var. angustifolia	Dragon Tree	Shrub, Tree	Full Sun to Full Shade	Mesic	https://garden.org
Chlorophytum Capense 'Variegatum' (v)	Spider Plant	Grass/Grass-like	Full Sun to Dappled Shade	Mesic	https://garden.org, https://www.rhs.org.uk
Carex Sylvatica	Wood Sedge	Grass/Grass-like	Full Sun to Partial Shade	Wet Mesic, Mesic	https://garden.org, https://pfaf.org

Table 1. List of plants. Mesic is a soil moisture regime referring to moderate moisture supply.

were exposed to full sun most of the time from April to August, leading to leaves with a lighter shade of green. Plant 3 and 4 were kept in a partial shadow area with little direct sun. After taken images from all four spider plants, plants 1 and 2 which were lighter in colour were put in a full shadow area for 24 hours. After this period, the four spider plants were photographed again. Only the green area of the leaves were observed with a patch size of 2 × 2 pixel. Lastly, a dead leaf which fell of was photographed after 24 hours. The leaf was brown and still moist.

Lastly, wild sedge was photographed in the local forest of Darmstadt. The camera was handheld and images were taken at about 1 m distance and from different perspectives. For each image a reference panel was placed at the side to correct the variance of sunlight. The patches have a size of 2 × 2 pixel.

4. RESULTS AND DISCUSSION

4.1 Time series of plants under stress

Over 18 days of observation, the signature of dracaena reflexa var. angustifolia (short: dracaena) does not change drastically (Figure 3). In general, stressed vegetation has a slightly higher red edge reflectance than healthy vegetation and shifts to shorter wavelengths. A tendency of higher values after day 1 in red edge wavelengths is visible in the signatures of plants 3 and 4. For plant 2 at day 2, only the bands from one camera were available, thus the red edge information around 705 and 740 nm is missing, which is why the curve appears different on that day and plant. Noticeable is the increase of reflectance for the plant without water (plant 2) and the plants without light (plant 3 and 4) in the red spectrum (550 nm to 700 nm). For the green spectrum, the reference plant (plant 1), and plant 2 and 3 tend to lower or unchanged reflectance, while plant 4 decreased the reflectance at the beginning but increased it at day 18.

The variance between days is higher than expected, represented by the reference signature (plant 1). In the NIR band the difference of reflectance is up to 0.33 (Table 2). The lowest variance is around 475 nm with a difference of 0.03 over 13 days of captures. In the visible light, the unwatered plant (no. 2) shows the highest difference in the red light with 0.11, deriving from an increase of 0.12 at day 1 to 0.23 at day 8. Generally, the absorbtion of blue and red light are used as power source for the photosynthesis, thus an increase of reflectance means less energy consumed by the plant. Plants 3 and 4, which received only water but no light, also show the most difference in the red light. The reflectance in the red spectrum of plant 3 varies between days without a clear tendency to higher or lower reflectance. The range of 0.11 in the blue light derives from the increase in day 5 to 0.15 reflectance, thus 24 hours after being watered. Lastly, plant 4 has a higher reflectance in visible light on day 18 than the days before. This could be due to plant adjusting for darker conditions and was overwhelmed by the sudden amount of light during capture.

	444	475	531	560	650	668	705	717	740	842
Dracaena 1	0.05	0.03	0.05	0.08	0.10	0.11	0.11	0.13	0.22	**0.33**
Dracaena 2	0.04	0.03	0.06	0.06	0.11	0.08	0.14	0.16	0.21	**0.31**
Dracaena 3	0.11	0.03	0.07	0.05	0.13	0.08	0.17	0.19	**0.24**	**0.24**
Dracaena 4	0.09	0.08	0.10	0.11	0.14	0.12	0.14	0.12	**0.16**	0.12

Table 2. Maximum difference of reflectance per wavelengths [nm] and dracaena. Bold: the overall highest difference per plant, underlined: the lowest difference.

Overall, the values vary greatly which is why a definite conclusion cannot be taken. Although calibrated with a reference panel, the values still include inaccuracies. The leaves were not all orthogonal to the camera such as the reference panel. Each leave can have different reflectance due to orientation to the sun and camera but also because of the absorbtion ability. Plants treat their leaves differently and can decide to drop leaves if they are no longer useful, even though the plant is still healthy. Thus, the signal varies between leaves within one plant.

For a better comparison, the NDVI was calculated for every day and plant (Figure 4). NDVI describes the change of red light absorbtion, which is important for the photosynthesis, and the rejection of too energetic NIR light. This comparison reduces the influence of variance between daily captures. Noticeable is the increase of NDVI values for plant 1 and the decrease for plant 2. Moreover, the lack of water seems to stress the plant more than the lack of light, based on the NDVI values. Generally, the health of the plants fluctuate over time. These span

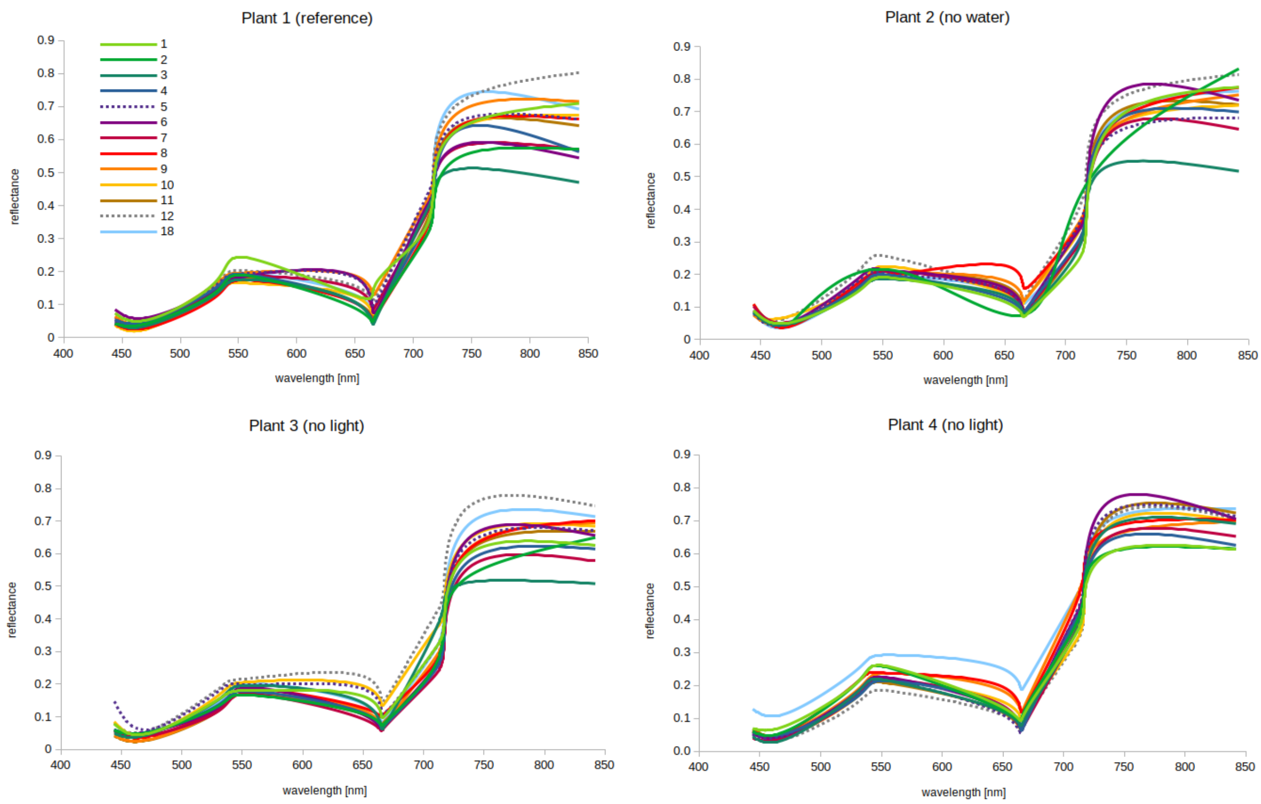

Figure 3. Spectral signature of plants under stress over 18 days, each line representing one day. Days 13 to 17 were skipped. Plant 1 was treated normally, plant 2 without water and plant 3 and 4 without light.The plants 1,3 and 4 were watered 24 hours before the images taken on day 5 and 12.

over NDVI values within 0.6 and 0.8, which can be interpret as healthy plants.

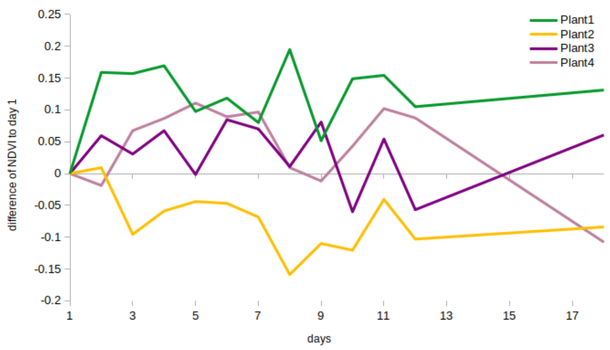

Figure 4. Change in NDVI of plants under stress referring to day 1. Days 13 to 17 were skipped.

4.2 Leaf colour change due to sun exposure

When a plant adjusts to a change in light level, the colour of its leaves change. The leaf appears lighter the more light it receives, as it rejects extra energy to protect itself. On the other hand, if it receives little light, the leaf will absorb more light, which will make it appear darker.

The leaves of spider plants have a white centre and green borders. The shade of green depends on the amount of light the plants is exposed to. Considering the white centre, the plant generally reflects more visible light than plants that are only green. During exposure to excessive light, the leaf appearance changed visible to a lighter green. The leaves quickly returned to a darker green after being placed in total shadow (Figure 5).

The results show the average values for the reflectance of spider plants that received the same amount of light (Figure 6). For example, the reflectance of plant 1 and 2 were averaged for the first day (T0) and the second day after 24 hours of full shadow (T1). As mentioned before, the measurements are influenced by many parameters, thus a completely unbiased measurement was not possible. However, the values between the spider plants exposed to full sun and the plants kept in partial shadow (plant 3 and 4), are closer to each other after 24 hours than before. Since the spider plants absorb more light in the shadow than in the light, the values for blue, green, and red light generally decrease as expected. However, with the exception of the reflectance at 531 nm (green), the reference spider plants (plants 3 and 4) also absorb more light than the previous day.

NDVI describes the difference between red and NIR and is widely used in the remote sensing community to indicate plant health in satellite and airborne images. The difference between red and NIR does not only shrink, when the health and likewise the NIR reflectance decreases, but also when the reflectance of red is higher than usual. If the leaves are lighter in colour, the reflectance of red is higher, thus the difference to NIR shrinks. In our case, the NDVI value slightly increases after the 24 hours of full shadow (Table 3). After 24 hours, both plants' NDVI values increased and have now only a difference of 0.01. It's unclear whether the reference plants experienced less stress and were healthier than before, tend to variations in light absorption

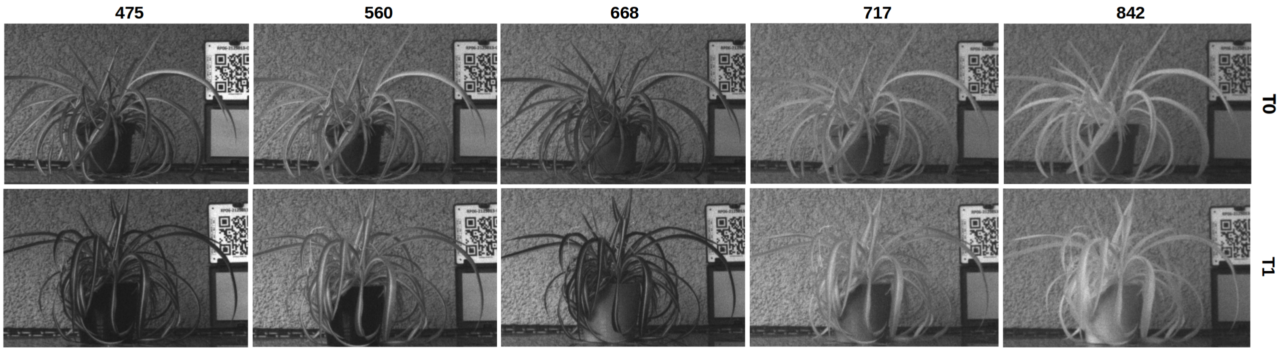

Figure 5. Exemplary visualisation of spider plants in the bands blue (475 nm), green (560 nm), red (665 nm), red edge (717 nm) and NIR (842 nm), for the first day (T0) and after 24 hours of full shadow (T1).

between days without a clear cause, or their health was unaffected and only a data inaccuracy took place.

Remarkably, the dead leaf has an NDVI slightly below the healthy leaves and a considerably higher NDRE value. NDRE is similar to NDVI, but instead of the red channel (668 nm) the red edge channel (705 nm) is taken. The values of NDRE are generally lower than expected. Compared to healthy plant leaves, this one is not quite as bright white. The green became brown and the white centre turned beige. As EOS Data Analytics, Inc. (2023) states, an NDRE range of 0.6 to 1.0 describes healthy and mature plants, in their case crops. NDRE values between 0.2 and 0.6 indicate unhealthy or immature crops. Following this guide, non would be classified healthy.

The indication of NDVI and NDRE do not distinct dead from healthy leaves, even though the signatures in Figure 6 clearly show differences. For this reason, we calculated a new index, named NDRER (Normalised Difference Red Edge Red), based on the strongest discrepancy in the signature between dead and living. The following equations is the NDVI equation with NIR changed to red edge.

$$NDRER = \frac{rededge - red}{rededge + red}$$

With NDRER, dead leaves are easier to distinguish because they have a noticeably lower value (0.11) than healthy leaves (0.61) (Table 3).

	NDVI		NDRE		NDRER	
	T0	T1	T0	T1	T0	T1
spider plant	0.58	0.61	0.35	0.41	0.59	0.61
reference	0.68	0.60	0.52	0.40	0.66	0.61
dead leaf		0.51		0.48		0.11

Table 3. Vegetation indices changing between T0 and T1 for the spider plants 1 and 2 (spider plant) and the spider plants 3 and 4 (reference). Dead lead was only captured ones.

4.3 Comparability between ours and USGS library

Finally, in the last experiment we captured carex sylvatica, called sedge, growing on the forest floor, at various distances and angles. The open access hyperspectral library by United States Geological Survey (USGS), offers among a variety of soils, mineral mixtures, liquids and vegetation, the spectral signature for sedge. This was first published by Kokaly et al. (2003).

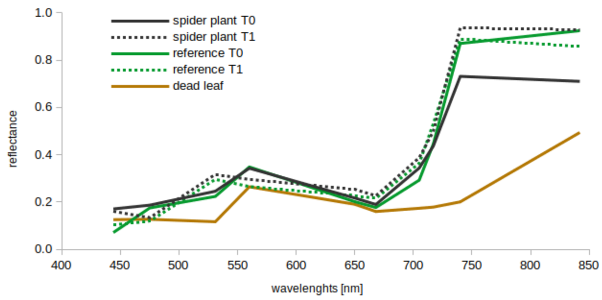

Figure 6. Spectral signatures of spider plants exposed to full sun and partial shadow over 4 months. Two spider plants received full sun over the summer (average, spider plant T0) and two reference spider plants received only partial shadow (average, reference T0). The spider plants were then put in full shadow for 24 hours (average, spider plant T1) while the reference plants was treated as before (average, reference T1). The dead leaf was captured 24 hours after detachment (dead leaf).

We summarised the original values per wavelengths into the the band definition by MicaSense (Figure 7). The maximum between ours and Kokaly et al. (2003) is in the NIR with 0.22, which could derive from different sensors, amount of light, distance between sensor, and object and plant state. Thereafter, we normalised both signatures to range from their minimum and maximum values. Now the signatures are similar. The greatest difference is at 560 nm, which represents green. Our data shows a reflectance of 0.19, and theirs of 0.11. Our data observes single leafs at 1 m distance, whereas the other data observed a large area from 2280 m above ground.

Regarding vegetation indices, in both NDVI and NDRER dead foliage is distinguishable from healthy plants (Table 4). Further, in both indices, our data shows 0.04 higher values than the data from Kokaly et al. (2003). These calculations were run on the non-normalised data. In conclusion, our findings are comparable with published work.

	NDVI	NDRER
sedge Kokaly et al. (2003)	0.70	0.62
sedge ours	0.74	0.66
dead foliage	0.25	0.15

Table 4. Vegetation indices for wild sedge.

Light reflectance can be used to distinguish objects such as ve-

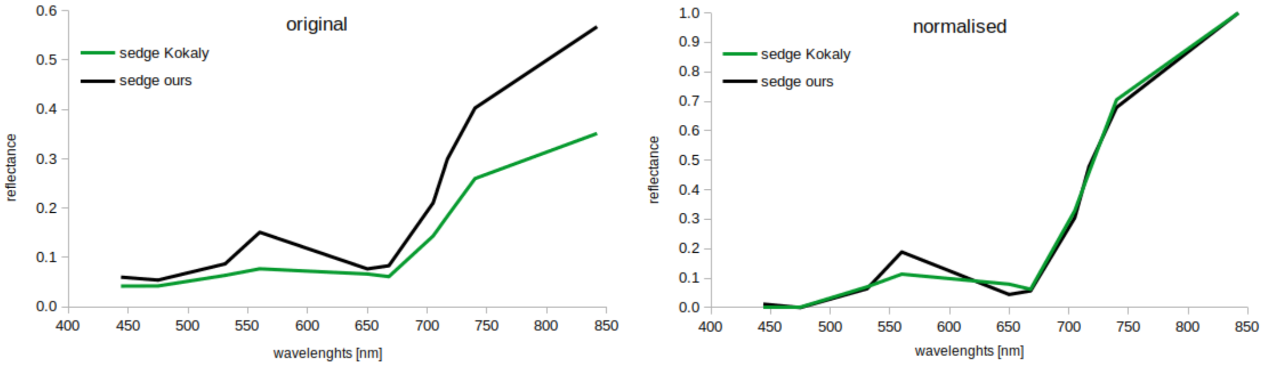

Figure 7. Spectral signature of sedge taken by us in a forest and by Kokaly et al. (2003). (left) original data, (right) normalised based on each minimum and maximum.

getation and non-vegetation. The intensity difference is the strongest in the red edge bands around 717 nm and 740 nm (Figure 6). Vegetation indicates low intensities in all cases in blue, green and beginning of red. In the transition from red to red edge, the intensities drop for dead leaves and increase quickly for healthy vegetation.

The MicaSense camera consists of separate lenses for each band, which is unproblematic if used as designed for UAVs and a distance of minimum 50 m. However in our case, we have distances around 2 m. This leads to difficulties in the image alignment. We noticed that one perfect calibration on a calibration image cannot be perfect for other images. This is because the distance to the objects varies and therefore needs another translation for each band. An individual transformation matrix was calculated if needed, but perfect matches were not always found. A dynamic registration of bands must be improved, as the function by opencv was insufficient and required more manual labour than it should have. Nonetheless, the approach showed comparable results with other work and can be used for close range tasks.

5. CONCLUSION

Multispectral images taken at close range with the MicaSense RedEdge MX dual camera system could detect changes caused by stress in plants. However, in distinct cases the vegetation indices were more useful. Generally, the capture setup, image processing and variances in daily plant health lead to high variances between captures. Additionally, each leaf has a different reflectance depending on the orientation to the sun and camera but also due to the absorption properties. Healthy and dead vegetation were clearly distinguishable in the red edge spectrum, which agrees with other work. The time series on dracaena reflexa var. angustifolia is still ongoing and may reveal stronger discrepancies in longer stress periods. Dynamic image fusion of 10 single bands with varying object distance and rapid sunlight changes must be improved with better object detection in images and light calibration during capture. The latter requires additional calibration for image regions within images and is currently restricted to whole images. A better calibration of sunlight and image registration will ensure higher quality of spectral signatures of close range captures.

6. ACKNOWLEDGEMENTS

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