Research Article

Received: 10 June 2021 Accepted article published: 30 August 2021

(wileyonlinelibrary.com) DOI 10.1002/ps.6623

Primarily tests of a optoelectronic in-canopy sensor for evaluation of vertical disease infection in cereals

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Abstract

BACKGROUND: Health scouting of crops by satellite, airplanes, unmanned aerial (UAV) and ground vehicles can only evaluate the crop from above. The visible leaves may show no disease symptoms, but lower, older leaves not visible from above can do. A mobile in-canopy sensor was developed, carried by a tractor to detect diseases in cereal crops. Photodiodes measure the reflected light in the red and infrared wavelength range at 10 different vertical heights in lateral directions.

RESULTS: Significant differences occurred in the vegetation index NDVI of sensor levels operated inside and near the winter wheat canopy between infected (stripe rust: 2018, 2019 / leaf rust: 2020) and control plots. The differences were not significant at those sensor levels operated far above the canopy.

CONCLUSIONS: Lateral reflectance measurements inside the crop canopy are able to distinguish between disease-infected and healthy crops. In future mobile in-canopy scouting could be an extension to the common above-canopy scouting praxis for making spraying decisions by the farmer or decision support systems.

Keywords: disease detection; leaf rust; stripe rust; sensor; vertical scouting; winter wheat

1 INTRODUCTION

In order to prevent disease outbreaks, field inspections should be done periodically throughout the growing season. When farmers notice disease symptoms, they need to spray immediately. However, manual crop scouting is time-consuming so that it allows only inspections at some locations in the field. If the weather conditions for disease development are favorable, fungicide spraying may be too late, especially if disease inoculum is present at unsampled areas in the field. In recent years, it has become common to use camera-equipped unmanned aerial vehicles[1,2] or tractors[3,4] to survey crops for pests and diseases. Depending on the vehicle and camera hardware, it is possible for the farmer to inspect cultivated areas at adequate time intervals to spot infections. Images can be evaluated visually for disease symptoms. Efforts also have been made to detect diseases by analyzing images automatically, for example using machine-learning algorithms.[5–7]

However, currently, sensors from unmanned aerial vehicle (UAV) and ground vehicle platforms can only inspect the upper visible leaves. Even if no canopy anomalies are detected from above, older leaves within the canopy that are not visible already may be infected. They will have been exposed to disease infections for longer. From fungal disease epidemiology,[8] it is well-known that plant diseases can spread rapidly to the higher and younger leaves (vertically) and to other plants in the neighborhood (horizontally). In particular, raindrops are responsible for splash-dispersing disease spores.[9] The first initial symptoms usually occur on the lower leaves near the soil.[10]

If the fungal infection on visible leaves is latent (time between successful penetration of the tissue by spores and the formation of visible symptoms) the lower leaves already may show disease symptoms. Because of the age of the lower leaves and their longer disposition to fungal colonization, it can be assumed that at this time the period of latent infection is over. Therefore, health status evaluation of the lower, older leaves gives information about the present infection potential and would bring a time advantage for decision-making by the farmer. It also could contribute to disease forecast models to make them more precise in disease outbreak forecast.

Green plant tissue can be distinguished from soil and from non-green, disease-infected, dead or senescent tissue by measuring and analyzing the reflectance in the red (R) and infrared (IR) wavelengths of light.[11–13] Healthy crop tissue reflects IR light and absorbs R light. The reflection of dead crop tissue or soil is nearly constant. Often, the Normalized Difference Vegetation

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Index (NDVI) = (IR – R)/(IR + R) is used for detecting changes in the canopy and growth anomalies.[14] Several optical sensors have been developed in the past years using R and IR wavelength ranges and made ready for the market, produced and sold by agricultural machinery makers. Several spot-spraying systems based on the on/off algorithm,[15] especially for applying nonselective herbicides, now are commercially available. Primarily in the field of nitrogen and herbicide application, those online sensors are controlling fertilizer spreaders and pesticide sprayers.

Here, we propose a sensor approach that enables inspection of the canopy from the inside, based on a new optoelectronic vertical sensor platform. For use under field conditions, the in-canopy sensor was developed with the following technical requirements:

- Performing lateral measurements of R and IR light
- A total of ten sensor levels with different distances from the soil surface for performing measurements inside and above the crop canopy
- Synchronized high-frequency ($100\ s^{-1}$) recording of the measurements
- The upper sensor level ten measures the total incoming radiation above the canopy and serves as a reference
- Depending on crop height, the lower nine sensor levels measure the R and IR reflection of the plant tissue, and the transmitted and incoming radiation inside and outside the crop canopy
- Rapid transferrance of the records to the tablet computer during operation
- Joint calculation of the readings of the various sensor levels and the highest level ten, which always is operated above the canopy to minimize the influence of the changing illumination conditions (sunny/cloudy) on the records.

The sensor was tested primarily on two common plant diseases in winter wheat – leaf (brown) rust (*Puccinia recondite* Rob. Ex Desm. f. spec. *tritici*) and stripe (yellow) rust (*Puccinia striiformis* West. f. sp. *tritici*). These diseases cause chlorophyll deficiencies on the plant tissue in the beginning of the infection. In later stages of the disease, the uredospore layers are built up on these lesions and at the end of the infection, the leaves die. The experiments were performed within the research project 'FungiDetect' financed by the German Federal Ministry of Food and Agriculture. A primary aim was to analyze whether the sensor revealed height-dependent differences in NDVI between infected and fungicide-treated healthy control plots.

2 MATERIAL AND METHODS

2.1 Optoelectronic in-canopy sensor

The in-canopy sensor, developed by the project partner TOSS GmbH (Potsdam, Germany), consists of a solid stainless-steel tube of 70 mm diameter. Five light diodes pairs (R and IR) are arranged circularly around the tube at ten ring levels, L1–L10 (Fig. 1, left). Each diode is set into the tube with a drill hole depth 1 mm and diameter 10 mm. Each light diode contains a diffusor and a TCS3200 light-to-frequency converter (TAOS, Plano, TX, USA). The diffusor consists of an opal glass pane of 3 mm thickness, which is put directly in front of the TCS3200 and homogenizes the passing light. The TCS3200 integrates a silicon photodiode array and a frequency converter on a single monolithic CMOS chip (R and IR part), which provides a square wave output with a frequency directly proportional to the irradiation flux measured at the photodiodes. The IR photodiode spectral responses had a sensitivity maximum for IR at 775 nm (full width half max: 100 nm) and for R at 660 nm (full width half max: 59 nm).

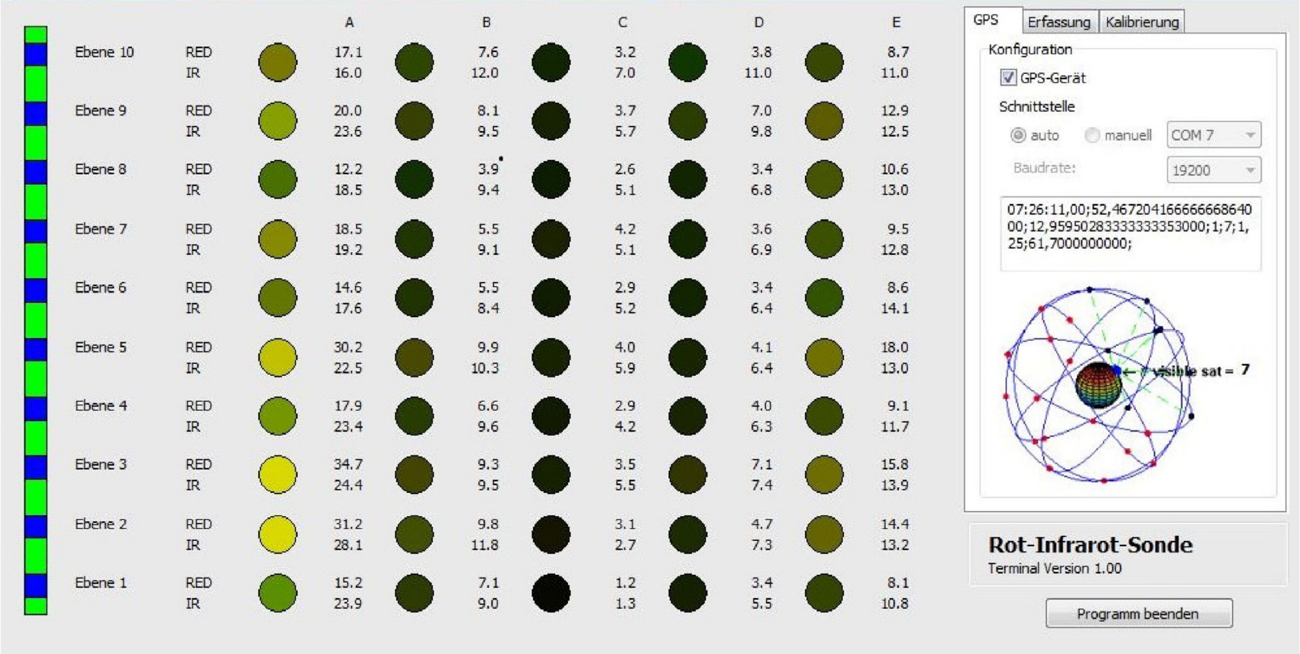
For the field tests, the in-canopy sensor was attached to the rear of a tractor using a three-point linkage on a movable device (Fig. 1, right). A swivel joint prevented the sensor from being torn off if it hit the ground while driving, a possibility resulting from the varying depth of the lanes in fields.

The records were transmitted to a tablet computer and saved, together with the GPS signal, in the software ROT-INFRAROT-SONDE TERMINAL v1.00 (Fig. 2).

2.2 Field trial for testing the in-canopy sensor

A trial of 15 plots with two treatments (seven plots infected with stripe rust, eight plots healthy and fungicide-treated) were arranged rectangularly (3 × 5) at the ATB Marquardt field station in 2018, 2019 and 2020 (Potsdam, Germany; 52° 28′ 00″ N, 12° 57′ 30″ E). The winter wheat variety 'Matrix B' was seeded, which has a resistance rating number of eight (highly susceptible) against stripe rust. The row distance was 0.12 m and seed rate was 350 seeds m^{-2}. Each plot had a size of 9 m × 9 m. The plots were separated by a vegetation-free track 3 m wide as passage route for the sensor-carrying tractor. Seven plots were inoculated

Figure 1. Section of the middle in-canopy sensor tube (left) and attachment to the rear of the tractor using a three-point linkage on a movable device during measurements in the plots (right).



		A	B	C	D	E
Ebene 10	RED	17.1	7.6	3.2	3.8	8.7
	IR	16.0	12.0	7.0	11.0	11.0
Ebene 9	RED	20.0	8.1	3.7	7.0	12.9
	IR	23.6	9.5	5.7	9.8	12.5
Ebene 8	RED	12.2	3.9	2.6	3.4	10.6
	IR	18.5	9.4	5.1	6.8	13.0
Ebene 7	RED	18.5	5.5	4.2	3.6	9.5
	IR	19.2	9.1	5.1	6.9	12.8
Ebene 6	RED	14.6	5.5	2.9	3.4	8.6
	IR	17.6	8.4	5.2	6.4	14.1
Ebene 5	RED	30.2	9.9	4.0	4.1	18.0
	IR	22.5	10.3	5.9	6.4	13.0
Ebene 4	RED	17.9	6.6	2.9	4.0	9.1
	IR	23.4	9.6	4.2	6.3	11.7
Ebene 3	RED	34.7	9.3	3.5	7.1	15.8
	IR	24.4	9.5	5.5	7.4	13.9
Ebene 2	RED	31.2	9.8	3.1	4.7	14.4
	IR	28.1	11.8	2.7	7.3	13.2
Ebene 1	RED	15.2	7.1	1.2	3.4	8.1
	IR	23.9	9.0	1.3	5.5	10.8

Konfiguration

☑ GPS-Gerät

Schnittstelle

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Rot-Infrarot-Sonde
Terminal Version 1.00

Figure 2. Screen shot of the in-canopy sensor software Rot-Infrarot-Sonde Terminal v1.00, GPS status/position as well as parameter settings (right) and the values of the R and IR measurements of 50 photodiode pairs (left).

in spring with 0.5 g spores mixed with 500 mL purified light mineral oil (Isopar M, no. 39 012; Cassens & Plath, Bremerhaven, Germany). Infection time was at evening, after sunset, to ensure dew formation, because the spores need water droplets for germination. The spore suspension was evenly spread using an electric microsprayer [PFS 2000 (Bosch, Stuttgart, Germany) operated by a PS-300 power station (IVT GmbH, Rohr, Germany)]. The eight control plots were treated two to three times with the fungicides to avoid disease occurrence.

2.3 Field measurements

The operation path of the in-canopy sensor was ≈1 m from the edge of the plots inside the crop stand. The assessment was performed once or twice per week (Table 1), beginning from BBCH 59 (end of heading), when the cereal crop did not increase in height anymore, until approximately BBCH 85 (soft dough), when ripeness with natural senescence of the leaves was clearly visible. The growth stage was determined according to the BBCH scale.[16] The measuring speed was 10 km h^{-1}. No plant damage resulting from contact with the sensor tube during driving was observed.

2.4 Statistical analysis of the measurements

For analyzing the R and IR reflection, only the measurements of three photodiode pairs at the corresponding levels were used, which were not exposed to the sun and thus not influenced by the direct sunlight during the sensor measurement. The measured values were influenced by the different intensity and spectral composition of the incident light of different cloud conditions. Therefore, a quotient between the reflection values of L1 to L9 and the reference L10 (reference measurement of the direct and indirect incoming light far above the canopy) was calculated.

Because of the decay of chlorophyll resulting from rust fungi infection, as a parameter for quantifying the height-dependent differences in disease incidence between the infected and control plots the NDVI was calculated for each of the lower nine sensor levels. The values from the three photodiode pairs (not influenced

Table 1. Date of sensor measurements and growth stage of winter wheat in the three years of field trials

Year	Date	BBCH	Year	Date	BBCH	Year	Date	BBCH
2018	18 June	83	2019	17 May	59	2020	26 May	59
				21 May	69		29 May	61
				3 June	71		3 June	65
				7 June	71		5 June	69
				14 June	73		12 June	71
				18 June	75		18 June	75
				21 June	77		26 June	77
				25 June	83		3 July	85

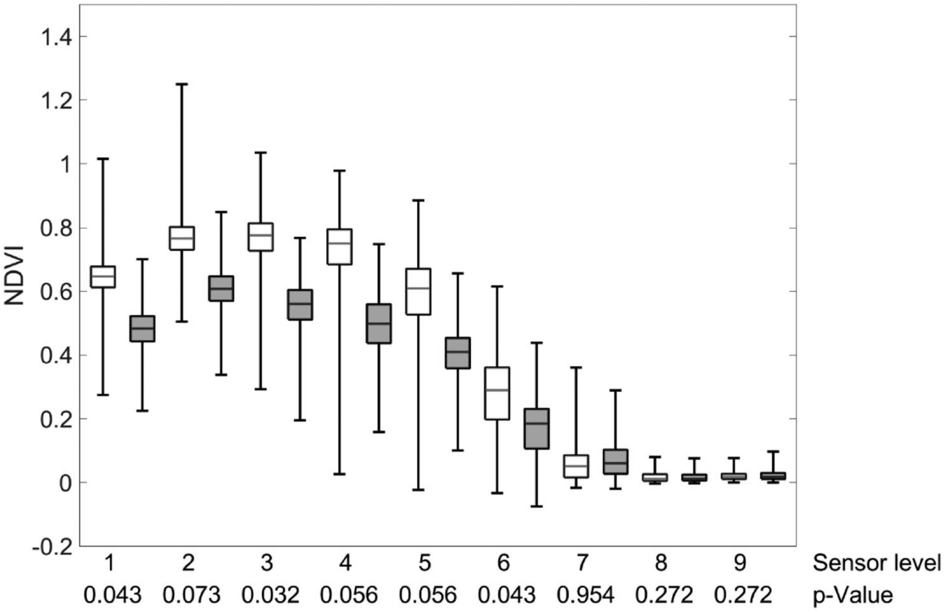

Figure 3. Box-whisker-plots of the NDVI for the sensor levels L1–L9 infected plots (gray boxes), control plots (white boxes) and *P*-value of the Mann–Whitney U-test, field trial 2018.

by direct sunlight) were averaged. Box-whisker-plots were generated for the diseased and healthy plots separately. They were displayed together in a graph for each measurement time. For testing, if the NDVI values were significantly different between the infected and healthy plots, Mann–Whitney U-test (Wilcoxon rank sum test) was performed using the software JMP13.2.1 (SAS Institute Inc., Cary, NC, USA).

3 RESULTS

3.1 Field trial 2018

Because of the completion date of the sensor system, only one measurement run over the infected and control plots was achieved in 2018 at the relatively late growth stage BBCH 83 (early dough). The sensor levels L1 to L4 were inside the canopy while operating the sensor system, with the L1 nearest to the soil at the bottom. The sensor levels L5 and L6 were operated near the canopy surface, whereas L7, L8 and L9 were outside the canopy. At the time of measuring, all leaves in the infected plots were completely infested by stripe rust. The control plots had no stripe rust symptoms at all; the color was almost yellow to light green, which was confirmed with the decomposition of the chlorophyll while ripening. The differences of L1 to L6 were significant between infected and control plots if a $P < 0.05$ is assumed (Fig. 3). The infested plots showed a lower NDVI compared to the healthy control plots. The NDVI values of sensor levels L7, L8 and L9 were close to zero with almost no differences between infected and control plots. The measurements of these sensor levels were not influenced by the reflection of the crop tissue.

3.2 Field trial 2019

The field mission in the year 2019 was conducted along a time series from 17 May to 25 June from low to high infection level, starting from BBCH 59 (end of heading) to BBCH 83 (soft dough). On the first three measurement dates, no significant difference occurred between the infected and control plots regarding the NDVI of all nine sensor levels (Fig. 4; for a better graphic arrangement, the *P*-values are not displayed). In L1, L2, L3 and L4, which were operated inside the crop canopy, significant NDVI differences occurred first with the fourth measuring date at growth stage 71 (watery ripe) with the lower NDVI in the infected plots. The other sensor levels outside the canopy (L7–L9) showed no significant differences, with an NDVI close to zero. At the following four measuring times, almost the same pattern occurred.

3.3 Field trial 2020

In test year 2020, artificial infection with stripe rust did not result in any disease infestation. This was probably a consequence of the low atmospheric humidity at the time of artificial infection and the resulting absence of dew during the nights. Because of the dry and hot spring and summer, the infected plots were disease-free for a long time. Later, natural infection of leaf rust occurred in the infected plots. In the control plots, fungicide application prohibited leaf rust infection and plants remained healthy and green.

Almost no significant differences occurred at all sensor levels (Fig. 5) until the sixth measurement date on 18 June (BBCH 75, medium milk). As an exception to the pattern, L5 and L6 showed significant differences at the second measuring time, which is not explicable based on their position relative to the canopy. From 23 June on at BBCH 77 (late milk), massive uredospore layers of leave rust occurred. From this time on, at the last two measuring times, the mean NDVI values of sensor levels L1 to L4 (operated inside the canopy) and L5 and L6 (directly at the canopy surface), were significant lower compared to the healthy plots. No significant differences were observed in the upper sensor levels L7, L8 and L9 (outside the canopy).

4 DISCUSSION AND CONCLUSION

In general, in all three years, the measurements of the vertical optoelectronic in-canopy sensor showed the same results. The calculated NDVI values of the various sensor levels represent the epidemiological disease development of stripe and leaf rust of the winter wheat in three different scales:

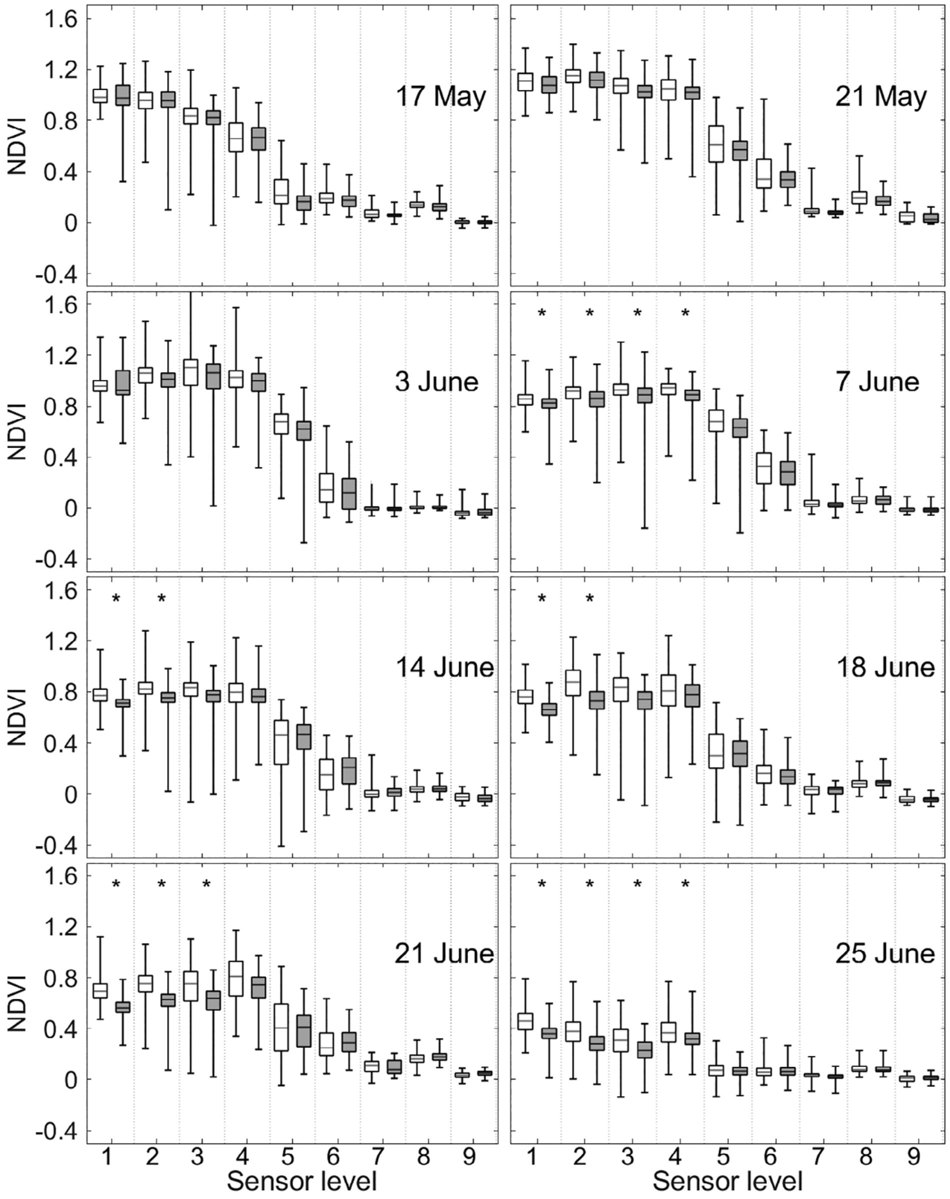

Figure 4. Box-whisker-plots of the NDVI for L1 to L9 infected plots (gray boxes), control plots (white boxes); *significance $P < 0.05$ of the Mann–Whitney U-test, field trial 2019.

- Vertical health statusWith proceeding disease epidemiology, the NDVI differences of L1 to L4 (operated inside the cereal canopy) became significant. Inside the crop canopy, these sensor levels were directly in contact or directly near the crop tissue. The values were lower in the infected plots compared to the healthy control plots. Later, the NDVI differences of L5 and L6 (operated at the canopy surface) were significantly different in the 2020 field trial. However, the NDVI values showed no significant differences at all measuring times for L7 to L9 (operated well outside the canopy). These sensor levels were not influenced by the reflection and light absorption of the plant leaves and leaf pigments, but rather by the incoming solar radiation.
- Horizontal health status The experimental design of the field trial can be partially compared with common practice. Stripe rust in particular occurs in patches in the start of epidemic development, and from a practical point of view, the artificially infected plots of the experiment can be considered to be akin to these patches. Healthy and diseased field areas are constantly changing, which in this study would be infected and control plots. Because of the GPS position recorded by moving through the plots with the sensor system, the R and IR reflectance measurements were allocated to the current plot. The sensor levels L1 to L4 inside the crop canopy were the important ones to differentiate the disease infection between the diseased and healthy plots.
- Time-dependent health status The sensor levels L1 to L4 were important for differentiating the epidemiological disease development. Additionally, L 5 and L6, which operated near the canopy surface, revealed significant NDVI differences over time in 2020 when leaf rust was present. The measurements of the above-canopy L7, L8 and L9 were not able to distinguish between diseased and healthy plots during the disease progress.

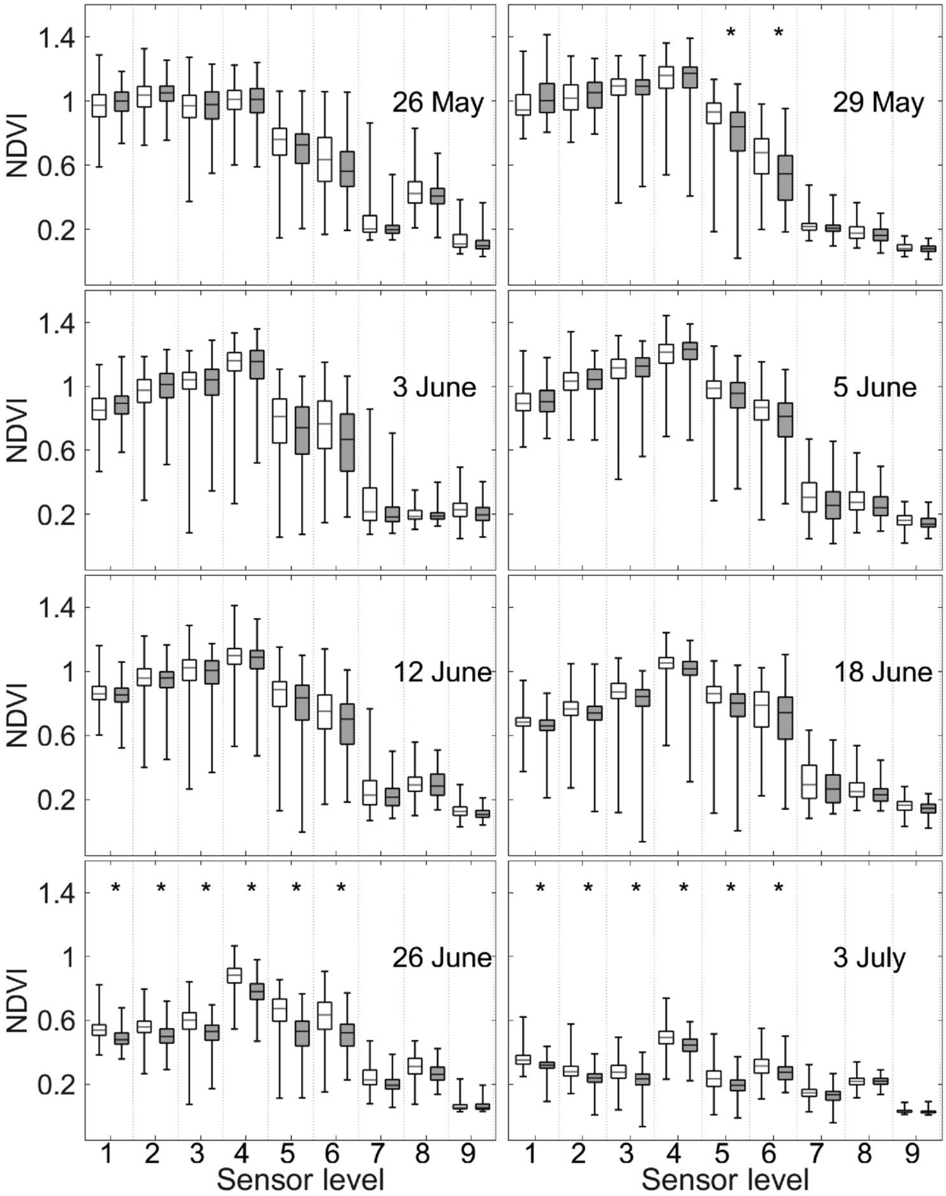

Figure 5. Box-whisker-plots of the NDVI for L1 to L9 infected plots (gray boxes), control plots (white boxes); *significance $P < 0.05$ of the Mann–Whitney U-test, field trial 2020.

If the development of the NDVI values at each measuring time in 2019 and 2020 is considered within each of the two treatments (infected and healthy) separately, the values at L1–L4 increased to a maximum at L4. First, this may correspond with the dependency of the chlorophyll amount in the plant tissue on the light intensity, which decreases with decreasing distance from the soil surface. Sensor level L4 was in contact with the most upper leaves and it is obvious that these leaves receive the maximum incoming light and therefore have the highest chlorophyll activity. Secondly the increasing NDVI sensed from L1 to L4 also may correspond later on with the chlorophyll decay in favor of cereal grain formation. The chlorophyll content decreases as the crop tissue gets older as happens in the lower part of the canopy, the so-called 'source sink'.[17] The NDVI values of L5 and L6, which were not in contact with the leaves while operating, further decreased. The NDVI of L7–L9 far above the canopy showed the lowest NDVI values, close to zero. There was almost no reflection being measured from the plant tissue anymore. This is due primarily to the lateral operation of the photodiodes which did not receive the reflected light from below.

If the time course of the NDVI is considered with proceeding measuring time in 2019 and 2020 treatment independently, the values of L1–L6 decreased in the infected as well as in the control plots from June onwards. This may correspond with the ripening process of the winter wheat. With increasing ripeness (senescence), degradation of the chlorophyll in the leaf tissue occurs. The NDVI values from L7 to L9 remained constant, near zero, at all measuring times.

Because of the mode-of-action of the in-canopy sensor, no shape parameters can be recorded, as is the case with camera imaging. Therefore, discrimination of the species of the present disease is not possible. Furthermore, it should be noted that the developed sensor cannot distinguish between dead material caused by the disease, natural senescence (ripeness) or other reasons. Making this distinction also is hard or impossible in common manual crop scouting, even by specialists. Even in the case of crop damage with other causes (e.g. nutrient/water deficiency, viral/fungal diseases, insect infestation), all spectrometric reflectance sensors available on the market provide only nonspecific information.

For practical aspects of fungicide spraying, it should be considered that at the finite fungicide application, which is mostly common in practice at flowering, it is mostly important to save the upper three leaves and the ear. It does not matter if the lower tissue inside the canopy is dead from diseases or from other reasons. In practice, farmers usually apply broad-spectrum fungicides or mixtures to control all fungal pathogens and also those that may occure after application within the time of effectiveness. Thus, at this time a species specific detection would not be necessary.

In a cereal fields with areal growth differences also the health status of the leave levels may differ. To know how many upper leaves are intact make sense if variable rate fungicide spraying is conducted. If only three or less leaves are intact and the spray liquid does not need to reach the lower tissue, the spray volume can be reduced site-specifically to cover them.

The present paper presents first results of the testing of this new sensor type. Investigations are just beginning and further research is necessary, especially regarding the relationship of the sensor measurements inside the crop canopy and the disease severity of the leaves.

ACKNOWLEDGEMENTS

The German Federal Ministry of Food and Agriculture funded the work in the joint project ‘FungiDetect’ (BLE 2815705615). We thank TOSS GmbH as the project partner who designed and constructed the R/IR vertical sensor system, and Andreas Garz for his contribution in designing the sensor, performing the test and measurement processing. We thank the colleagues of the Department Engineering for Crop Production Antje Giebel for doing statistical analysis, Uwe Frank and Andre Hamdorf for doing the measuring campaigns and Franziska Gleiniger for formatting the text.

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Pest Management Science published by John Wiley & Sons Ltd on behalf of Society of Chemical Industry.