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Target-orientated and precise, real-time fungicide application in cereals

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Real-time application technologies based on the target crop, crop surface area and biomass using non-contact sensors for precise fungicide spraying in winter wheat have been developed in a joint research project. The decision support system proPlant expert.classic and the internet-version proPlant expert.com (proPlant GmbH) suggest appropriate fungicides and dosages for certain infection scenarios of eight important leaf and ear diseases of winter wheat. The Precision Farming Module "Fungicide", which runs on the on-board terminal in the tractor cabin, controls the spraying process. During the spraying process, the module defines the local target application amount using a local ultrasonic sensor value as an input parameter.

Winter wheat field experiments were conducted in 2013 and 2014 (Agri Con Co., ATB) to analyse the relationship between the sensor values (ultrasonic and camera) and the leaf area index (LAI) and biomass crop parameters that are important for a locally adapted and variable fungicide application rate. Measurements were performed several times during the vegetation period at sampling points that were visually selected based on crop density. Regression analyses showed that after technical changes in 2014, a linear relationship was obtained between the sensor values and the two crop parameters.

Keywords
biomass, leaf area index, fungicide, sensors, cereals

The joint research project "FungiPrecise", which is funded by the German Federal Office for Agriculture and Food (support code: 2814704511), was initiated in Fall 2012 to develop real-time application technologies based on the target crop, crop surface area and biomass using non-contact sensors for precise fungicide spraying in winter wheat. The research project consists of three subprojects:

- The Precision Farming Module "Fungicide" (proPlant GmbH),
- An ultrasonic-controlled field sprayer (Agri Con Co.) and
- A camera-controlled field sprayer and project coordination (Leibniz Institute for Agricultural Engineering, ATB).

Recently, proximal sensor technologies have been introduced into practical farming, especially in the field of nitrogen application. At least seven sensors were commercially available as of 2011 (Reckleben 2010, Ehlert 2011). These technologies are based on sensors that mainly detect canopy reflectance. In the field of plant protection, a few sensor-based, real-time technologies in weed control (Peteinatos et al. 2014) and growth regulator application (Volk et al. 2010a) are commercially available; however, solutions for fungicide application remain limited.

A common practice in crop protection is the uniform application of fungicides over an entire field. At the beginning of fungal epidemics, the pathogens typically develop in patches (Campbell

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and Madden 1990, Hughes and Madden 1995). Consequently, fungicide application is not required in disease-free subareas.

If disease symptoms are visible to the human eye, a severity estimation using a spatial sampling scheme can be performed. However, this is very time consuming. Therefore, reports of site-specific fungicide application that are based on the visual assessment of diseases and the subsequent generation of disease maps are only performed in experimental sites (Secher 1998, Bjerre 1999). If weather conditions are favourable, diseases spread rapidly over an entire field and an immediate decision on disease control is needed, which becomes problematic if a visual assessment has been performed.

Automatic disease detection, before the disease incidence reaches a particular threshold, would help to provide information about the parts of fields infected by disease. Sensor technologies have to replace visual disease assessment. These sensors must detect diseased plant parts rapidly and reliably in the early stages of disease development and in real-time while in the field. Various approaches have been used in research to detect plant disease symptoms, and Bock et al. (2010) published a review paper on useful methods.

Because there are no sensor-based technologies on the market for automatic disease detection before the pathogens reach critical thresholds, Dammer and Ehlert (2006) developed an alternative method for optimising fungicide application in real-time. The idea was that the target of a fungicide is not a certain area, which contrasts with the recommendation made by fungicide manufacturers who typically specify product application on a per hectare basis. In precision plant protection, the target is not the “hectare”; the target is the crop to be protected against pathogen infection. In practice, however, fungicide application to sparse canopies results in fungicide loss to the soil. Therefore, the application rate is adopted according to the local plant surface (Leaf Area Index, LAI) or biomass, respectively. When soil and relief conditions are heterogeneous within a field, it is likely that crop growth is also heterogeneous. This is because of differences in water and nutrient availability. The strategy in precision fungicide spraying is to reduce the fungicide application rate in areas with low LAI/biomass by maintaining a constant concentration (recommended on the product label by the manufacturer) of liquid in the sprayer tank. The entire plant surface has to be covered equally by the spray liquid, which is especially important in the case of protective fungicides. In the case of systemic fungicides, a certain concentration has to be built up in the plant to ensure the pathogen is killed. Therefore, LAI and aboveground biomass are important parameters in precise, variable-rate fungicide application. To control a field sprayer using a sensor, the sensor signal must correlate with LAI or plant biomass.

However, the target-orientated (crop) spraying technology does not consider differences in disease occurrence (pathogen infection) in field areas with differences in crop biomass. Various fungal diseases respond differently in various dense canopies. For example, the infection severity of powdery mildew (*Blumeria graminis*) is higher in high-density spring and winter cereals (Sentelhas et al. 1993). Stripe rust (*Puccinia striiformis* West. f. sp. *tritici*) occurrence is correlated with high temperature (Park et al. 1992) because low crop density areas warm up faster. However, variations have been observed in leaf blotch disease (*Septoria tritici* Rob. Ex Desm.). For example, Bjerre (1999) found a negative correlation between disease severity and crop density, whereas Broscious et al. (1985) and Sentelhas et al. (1993) reported higher disease infection in dense canopies if precipitation was absent. In addition, different fungal pathogens may occur simultaneously within a field, which has resulted in farmers spraying broadband fungicides to control all current and potential diseases.

In addition to the heterogeneity in plant surface and biomass, the economics of fungicide use is an aspect that needs consideration. A well-established crop produces higher yield than a crop suffering from poor nutrition or water stress. A different nutrient and water supply results in spatial heterogeneity of crop yield. If one considers different yield expectation areas within a field, the expected profit also varies. The contribution to the expected profit is higher in high yield subareas compared with low yield areas. Therefore, target-orientated and variable-rate fungicide application based on LAI or biomass optimises the use of production inputs and reduces operation costs and energy input. In addition, the impact of biocides on the environment is reduced.

The CROP-Meter, developed at the Leibniz Institute for Agricultural Engineering (ATB), was the first commercially available mechanical sensor for precise fungicide application in cereals. The sensor consisted of a horizontally pivoted metal rod that was deflected by the bending moment of stem resistance. The sensor signal was correlated with plant surface area (Dammer and Ehlert 2006) and biomass (Ehlert and Dammer 2006), which served as parameters to vary the application amount. In long-term field trials, average fungicide savings of 22% were achieved (Dammer and Ehlert 2006). In addition, a greater area was sprayed using one sprayer tank compared with conventional spraying, and the spraying equipment operated at higher capacity. Therefore, machine costs were reduced. In addition, no yield reduction or higher occurrence of plant diseases was found in comparison to conventional treatments (Dammer 2005a).

The information from CROP-Meter (sensor) and the decision support system proPlant expert.precise (map) was combined in a previous research project to provide a real-time spraying system with map overlay (Dammer et al. 2009). The proPlant expert.precise prototype was used to estimate infection risks from fungal diseases using weather and field-specific data for up to three management areas with different yield expectations. The system generated a spraying map with different fungicide dosages. Compared with conventional uniform spraying, the CROP-Meter with map overlay treatment resulted in approximately 33% fungicide savings (Dammer et al. 2009).

The contactless ultrasonic and camera sensors can be operated more easily compared with the sensor CROP-Meter that was in contact with the crop during spraying. Therefore, spraying technologies will be developed within the FungiPrecise project based on ultrasonic and camera technology. Field trials related to the “FungiPrecise” project were conducted in 2013 and 2014 to investigate the relationship between the sensor signal and the two plant parameters, i. e., biomass and LAI.

Material and methods

The sensors used in this project are able to provide two-dimensional (camera) and three-dimensional (ultrasonic) signals from the scanned area. In contrast, spectrometric canopy reflectance sensors, which are used operationally for nitrogen application, provide mixed signals of soil and plant (one-dimensional). Camera and ultrasonic sensors are small and can easily be attached to agricultural machines.

Decision support system and dosage algorithm

The most important influence of fungal infections on plants in the field is the weather. Decision support systems such as proPlant expert.classic can provide farmers with information about disease infection probabilities (i. e., days with high, low and no infection risks) and suitable application times, fungicide products and application rates (Volk et al. 2010b). These systems are especially useful for determining the appropriate time to start spraying in case of latent pathogen infestation. This happens if the fungal infection has already started but symptoms are not yet visible. These systems can be used to schedule fungicide application based on demand. This avoids ineffective applications and possible yield reductions, which can occur after fungicide application (Böttger 1984, Martin 1986). In addition to weather data, other parameters that influence pathogen infections have been incorporated into these systems, such as cultivar, sowing date, plant density, growth stage, nutrition and soil dryness. In Germany, proPlant expert.classic is widely used by farmers and consultants for field-specific decisions, not only in cereals but also in other field crops. Therefore, proPlant expert.classic was used in this project to provide the basic information mentioned above for the application of fungicide to winter wheat.

The sensors provide LAI and biomass information. The correlation between the sensor values and the actual LAI and biomass is used to develop a simple, universal and usable dosage algorithm (for a realistic farm condition). This programming will be completed by the proPlant company. The Precision Farming Module "Fungicide" has to be ISOBUS conform code to control various commercially available field sprayers.

Ultrasonic sensor-controlled field sprayer

Ultrasonic sensors send out short acoustic pulses. In sugar cane (Portz et al. 2013), cotton and soybean (Sui et al. 1989), corn (Shresta et al. 2002) and cereals (Reusch 2009), ultrasonic sensors delivered promising results with respect to the measurement of various plant parameters such as height and biomass. The research work in this subproject is carried out by the company Agri Con. For the future spraying experiments one sensor (Figure 1) will be attached to each section of the spray boom to allow independent control of the boom sections.

In the experiments conducted in 2013 and 2014, the correlations between the sensor signal and crop biomass and LAI were determined. The time-of-flight of the various echoes was measured and an "ultrasonic height" was subsequently calculated.

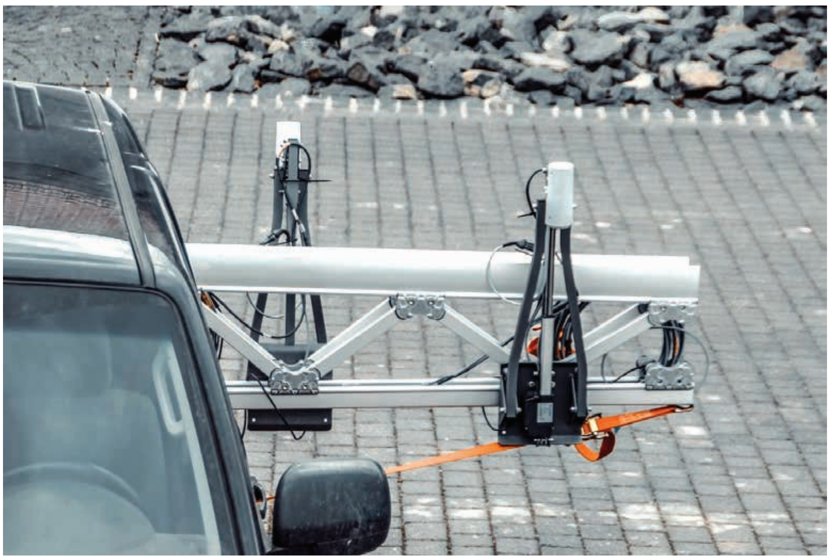

Figure 1: Test prototype of the ultrasonic sensor (Agri Con)

Camera-controlled field sprayer

In this subproject performed by ATB, a camera sensor is combined with a field sprayer to perform a variable-rate fungicide application. The effect of the camera sensor-controlled fungicide application on crop yield and disease occurrence will be evaluated in field strip trials in the coming years.

In the field trials in 2013 and 2014, the 3-chip CCD multispectral camera sensor (Figure 2) simultaneously captured red, infrared and green images. The red (R) and infrared (IR) images were used to calculate a grey scale image of the Normalized Differential Vegetation Index (NDVI = (IR - R)/(IR + R)). In a calibration step, a threshold was determined to separate the green crop from the background. All image pixels were set to white if a particular NDVI exceeded the threshold. The percentage of those pixels represented the coverage of the green crop.

The background in the camera image could be mature or dead plant tissue. This occurs particularly in field areas with sparse crop growth. These areas can mature up to one month earlier compared with well growing areas with dense crop canopies (Dammer 2005a). There is no need to protect mature crop tissue with fungicides against pathogen infection.

This type of camera sensor system was recently used for detecting plant parameters in canola (Dammer 2005b), head blight (*Fusarium* spp.) in winter wheat (Dammer et al. 2011) and weed infestation in winter barley (Dammer et al. 2012).

Figure 2: Test prototype of the camera sensor (ATB) in the field trials; operation height: 2.50 m above ground on the left side in the driving direction

Results and discussion

Field measurements

The 2013 and 2014 experiments managed by Agri Con and ATB were conducted in winter wheat fields of local agricultural farms to analyse the relationship between the crop parameters and the sensor signal. Experiments presented in this paper were conducted in the following two fields:

2013 – Ostrau I (longitude E13.1103, latitude N51.2291) – Agri Con
Dabrun I (longitude E12.7117, latitude N51.8204) – ATB
2014 – Ostrau II (longitude E13.1103, latitude N51.2299) – Agri Con
Dabrun II (longitude E12.6967, latitude N51.8354) – ATB

Sampling points with different crop growth were selected manually for each measurement run. The parameters measured along these sampling transects included

- Sensor signal (ultrasonic sensor, camera sensor),
- LAI, using the hand held SunScan® (Delta-T Devices Ltd, Cambridge, GB) device,
- Biomass within the sensor detection area.

The minimum and maximum crop parameter values that were measured in one of the experimental fields in 2013 are presented in Table 1 and Table 2 to show the variability in values.

Table 1: Minimum and maximum values of the crop parameters measured in Ostrau I (Agri Con) field trial 2013 using an ultrasonic sensor detecting area of 1.0 m x 0.5 m (0.5 m²)

Date	Ultrasonic height [cm]		LAI		Biomass [kg per 0.5 m²]		Growth stage [BBCH]	
	min	max	min	max	min	max	min	max
06.05.	23	57	1.9	5.3	0.28	0.48	33	33
21.05.	37	64	1.6	7.7	0.39	1.28	37	37

Table 2: Minimum and maximum values of the crop parameters measured in the Dabrun I (ATB) field trial 2013 using a camera sensor detecting area of 2.2 m x 1.4 m (3.08 m²)

Date	Coverage level [%]		LAI		Biomass [kg per 3.08 m²]		Growth stage [BBCH]	
	min	max	min	max	min	max	min	max
15.05.	68	98	2.2	5.2	3.68	6.72	33	34
05.06.	46	99	2.5	6.0	4.9	11.62	51	61
19.06.	40	99	0.4	3.8	4.38	10.86	69	71
04.07.	19	94	1.8	4.7	-	-	57	87

There was high variability in the sensor values and crop parameters in both field experiments. There were distinctive differences in crop development according to the BBCH code (Lancashire et al. 1991), especially in the Dabrun I field trial, e.g., at the last measuring date, where the crop corresponded to the plant developmental stage BBCH 87 in the sparse canopy areas and to BBCH 57 in the dense canopy areas.

Relationship between the sensor (ultrasonic and camera) values and crop biomass and LAI

The relationships between the sensor values and the crop parameters measured in the 2013 experiments are illustrated in Figures 3 to 6. There was a positive relationship between the sensor values and biomass and LAI in the Ostrau I field trial. A significant linear regression was not found because of high variability in the data.

At first the crop coverage level determined using the camera sensor increased proportionally to the LAI and biomass. Afterwards, the coverage level remained constant between 90% and 100% from a certain biomass/LAI value on (biomass > 6 kg, LAI > 3). This indicates that in areas with a high crop density the camera did not accurately estimate the biomass and LAI values. The relationship between the coverage level and biomass could not be investigated at the last sampling time (4th of July). Because of technical problems the biomass was not determined.

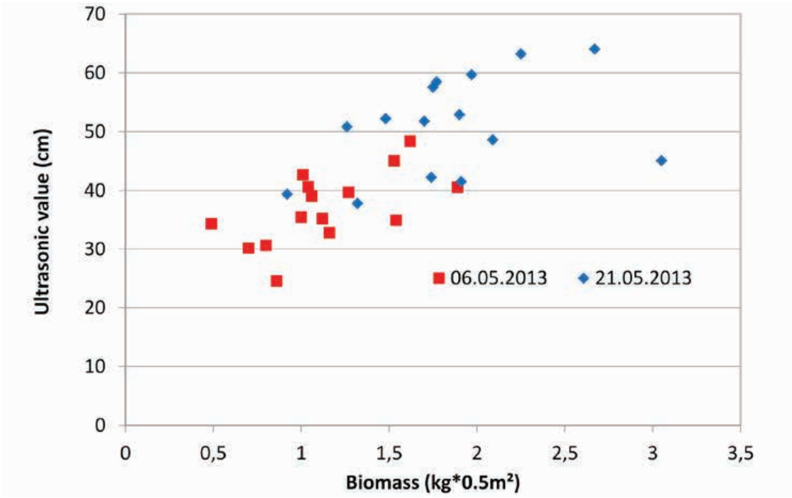

Figure 3: Relationship between the ultrasonic value ("ultrasonic height") and biomass at the Ostrau I field site at two sampling periods in 2013

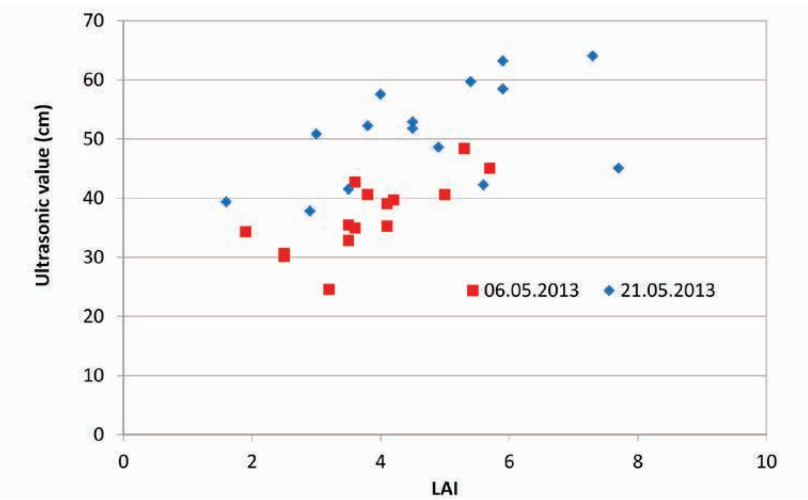

Figure 4: Relationship between the ultrasonic value ("ultrasonic height") and LAI at the Ostrau I field site at two sampling periods in 2013

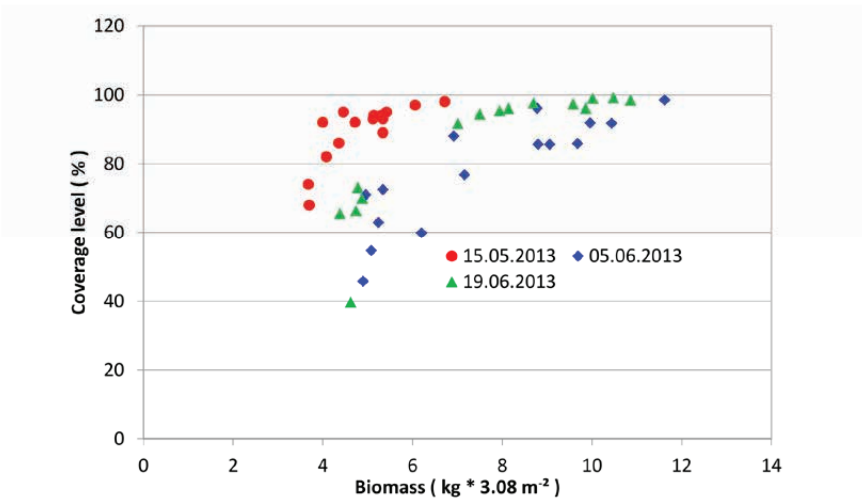

Figure 5: Relationship between the camera value ("coverage level") and biomass at the Dabrun I field site at three sampling periods in 2013

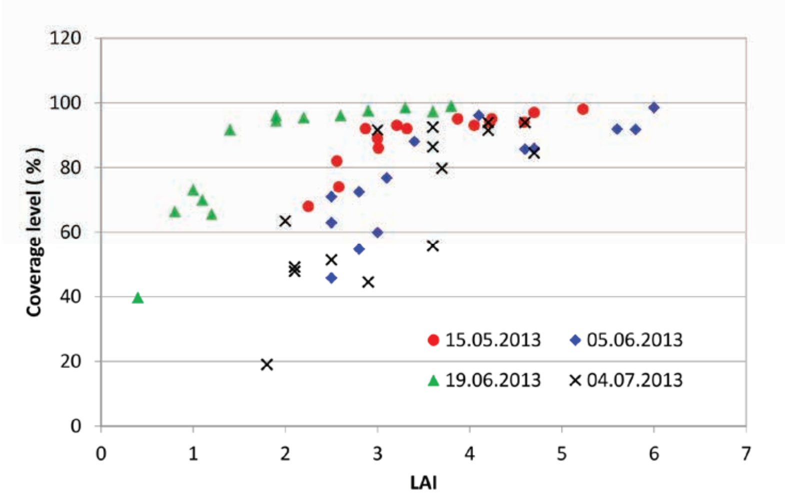

Figure 6: Relationship between the camera value ("green coverage level") and LAI at the Dabrun I field site at four sampling periods in 2013

Technical changes were made after examining the results from 2013. For example, the reason why the coverage level measured by the camera sensor remained constant (near a maximum value of 90 to 100 %) is related to the fact that the camera measurement is a two-dimensional projection of a three-dimensional cereal crop architecture (several leaf layers). In dense crop canopies, the sensor can only detect the upper leaves. A reason for the high scattering of the data might be related to the camera itself; the objective lens was a SIGMA fisheye 8 mm (F3.5 EX DG), which was used to capture an area as large as possible from a fixed distance. However, the image pixels at the edge of the image were deformed, which severely influenced the estimated coverage level. Therefore, an aspherical

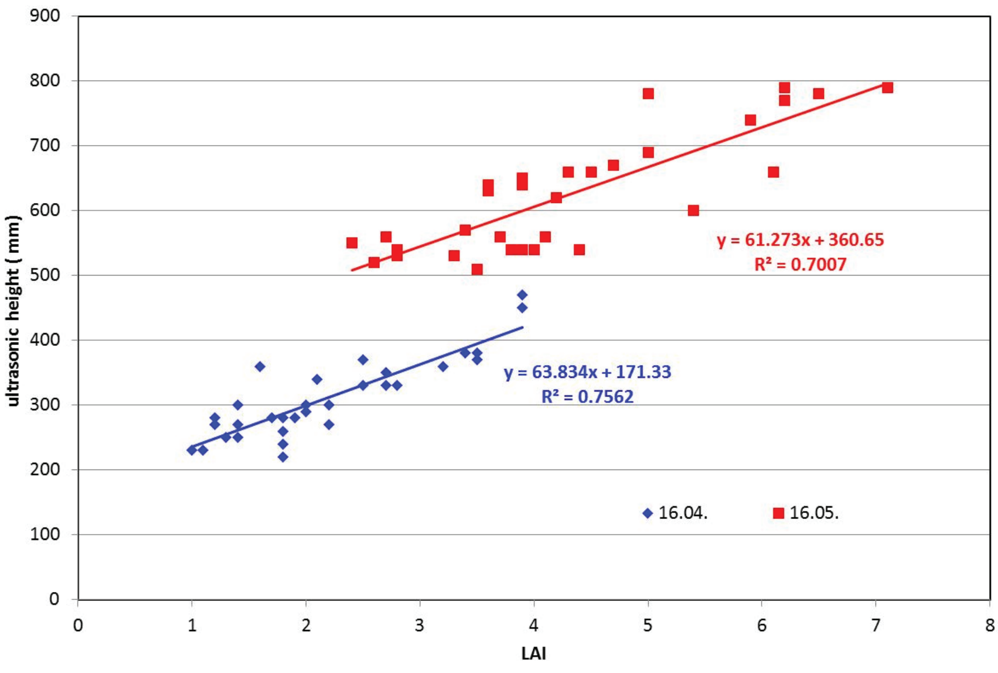

Figure 7: Relationship between the ultrasonic value ("ultrasonic height") and LAI at the Ostrau II field site at two sampling periods in 2014

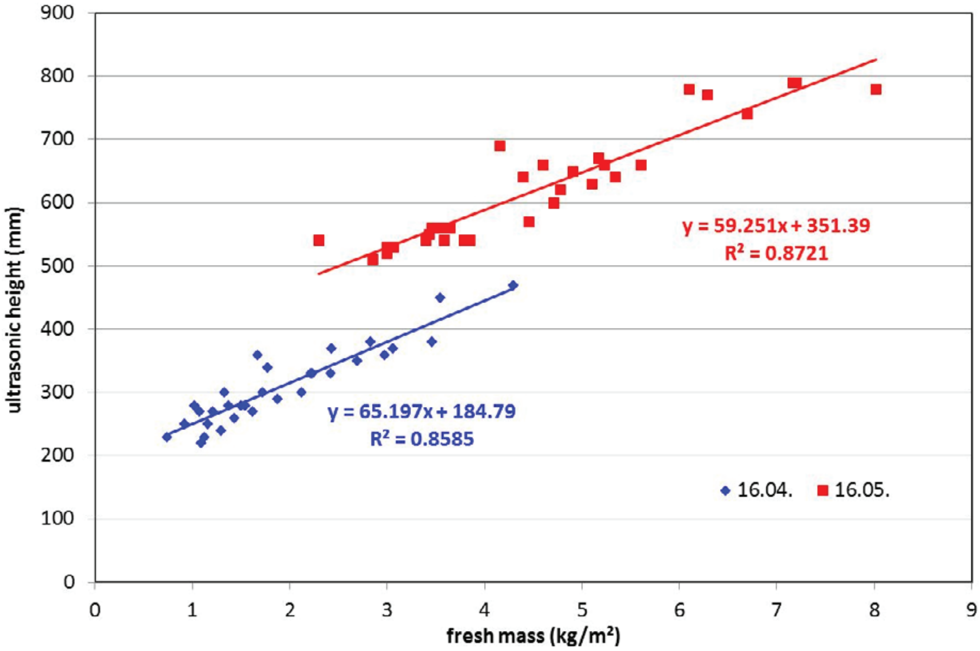

Figure 8: Relationship between the ultrasonic value ("ultrasonic height") and biomass at the Ostrau II field site at two sampling periods in 2014

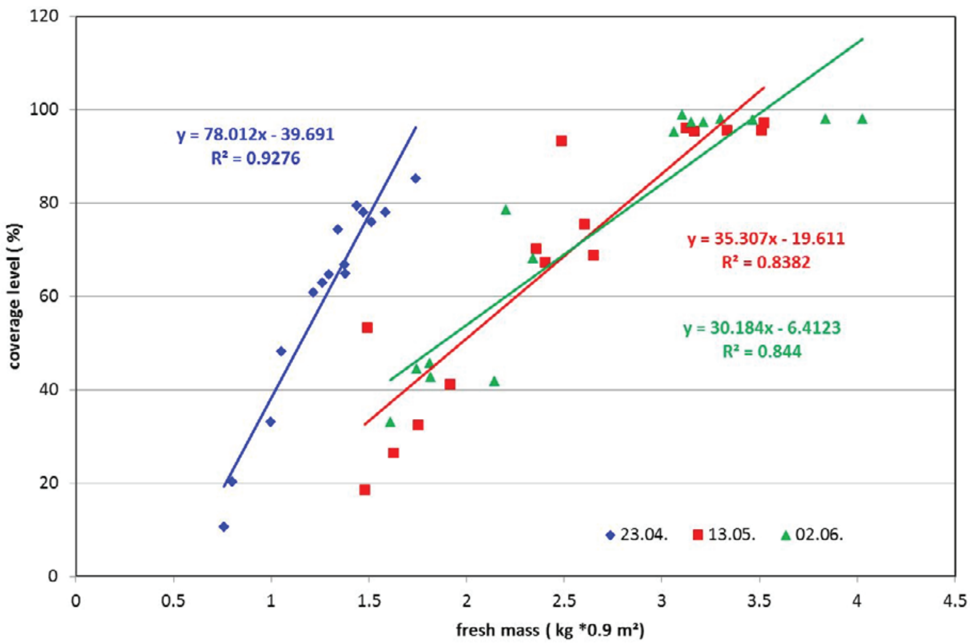

Figure 9: Relationship between the camera value ("green coverage level") and biomass at the Dabrun II field site at three sampling periods in 2014

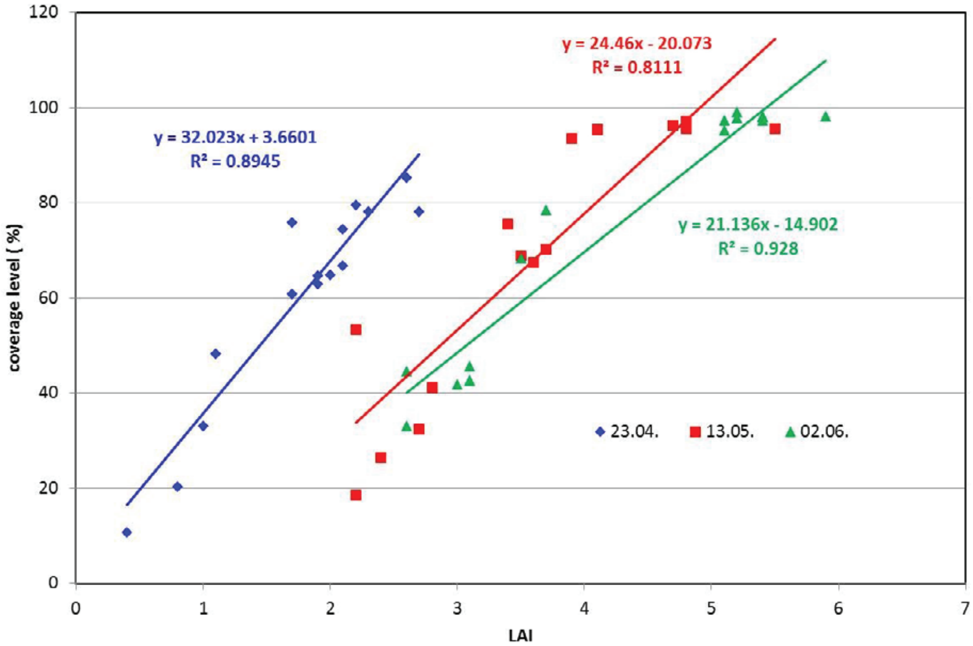

Figure 10: Relationship between the camera value ("green coverage level") and LAI at the Dabrun II field site at three sampling periods in 2014

SIGMA 14 mm (HSM 1:2.8 D) objective with a smaller measuring area (about 0.9 m²) was used in the field trials in 2014.

The relationships between the ultrasonic and camera sensor values and the crop parameters LAI and biomass measured in the 2014 experiments are illustrated in Figures 7 to 10. In contrast to year 2013, because of the shape of the point cloud, significant linear regressions were observed.

There was a significant linear relationship between the sensor values and plant LAI and biomass in the 2014 experiments. The coverage level estimated by the camera sensor at the last two sampling periods increased proportionally to biomass and LAI for lower density sampling points and remained constant between 90% and 100% for a given biomass and LAI value on for sampling points with denser crop canopies. This was similar to the results from 2013.

Conclusions

The results indicate that the sensor values can be used as an input signal for the variable rate sprayer system to adapt linearly the local spray amount to LAI and biomass (dosage algorithm). In precise fungicide spraying, information about the green coverage level is required, because dead plant material does not need protection against fungi anymore. But at later BBCH stages, the coverage level remained constant between 90% and 100% from a certain LAI and biomass level on. Sensor fusion, i.e. the combination of an ultrasonic sensor with a camera sensor, would certainly improve the LAI and biomass estimation at later BBCH stages. Future research will be conducted in order to prove this hypothesis.

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