Theses of Doctoral (PhD) Dissertation

DETECTION OF DIFFERENT STRESS FACTORS WITH SENSOR MEASUREMENTS IN PRECISION CORN FARMING

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1. INTRODUCTION

In today's modern agriculture, digitalization and data-based decision-making are playing an increasingly important role in achieving the goals of productivity and sustainable agriculture. Precision agriculture and the rapid technological development of recent years have enabled users (producers, researchers, development engineers) to collect real-time, precise and high-accuracy data on the current state of the cropland, vegetation and soil. Remote sensing based on agricultural UAVs, and within this, the use of multispectral camera systems, is becoming increasingly widespread. With the help of GIS software and digital platforms, we can perform more complex analyses and comprehensive assessments of the areas under study. Multispectral cameras mounted on agricultural drones have become significant tools for identifying and assessing plant diseases and plant stress of various origins, as well as for mapping out discrepancies in the field.

By integrating remote sensing-based GIS (Geo Informatics System) or geographic information systems, farmers can obtain accurate and detailed information about their area, based on which interventions can be timed, scheduled and optimized. The systems are also suitable for the joint management of information from different data sources. These include soil property indicators, plant parameters, meteorological data sets or the values of various vegetation indices from multispectral vegetation maps, e.g. (NDVI, GNDVI, LCI). The combined use of the data can even optimize production costs and input material use, detect water shortages and plan irrigation, and minimize negative environmental impacts. Based on the different spectral properties of plants, one of the most significant topics within the field is the identification of plant diseases (identification, extent, severity assessment) and plant stress status. The application, development and optimization of plant protection methods, as well as prognostics, are all key areas, especially if we want to apply the principles of IPM (Integrated Pest Management). Multispectral cameras are suitable for early diagnostic purposes based on VIS-SWIR technology. This technology can be especially effective in identifying types of plant diseases that affect chlorophyll or carotenoid content in some way, and also produce symptoms based on necrosis or chlorosis (yellowing/browning, fading, various color changes). They are also suitable for detecting other significant stress factors: e.g. in particular for identifying nutrient and water deficiencies or possibly recognizing the presence of pests.

With the help of data sets collected by multispectral cameras, vegetation indices can be created in a GIS environment and these can be further analyzed. Today, the most widely used vegetation index is the NDVI (Normalized Difference Vegetation Index). The use of vegetation indices can be extremely effective for monitoring spatial differences and variations. They can also be used well for long time series mapping processes, as they provide objective and comparable data. Agricultural UAV-based surveys play a significant role not only in precision agriculture, but also in the field of plant protection surveys and interventions. Multispectral-based plant stress and plant pest identification is a dynamically developing field, which is the subject of numerous publications, research and development.

1.1. Aim of the study

Detection of plant pathogens and monitoring their spread are key to achieving sustainable agricultural goals. Plant pests cause serious damage to both the quality and quantity parameters of the crop. Combining modern remote sensing and data analysis technologies allows for the rapid and accurate assessment of large areas. The main objectives of my research include the examination of the applicability of remote sensing technologies and their methodological development for identifying plant diseases and assessing infection levels and disease extent.

The main objectives of my research are:

1. Examination of spectral properties of infected and healthy plant stands: Identification of lesions caused by various plant pathogens based on remote sensing data. Accurate and precise data collection based on multispectral UAV technology. Detection of early stages of infections, determination of pigment ratio changes, water content changes and tissue destruction caused by symptoms.
2. Data analysis and processing: Efficient processing methodology for large amounts of data and its development. These can provide the basis for the development of new algorithms and the rapid detection of data-based differences.
3. Spatial data distributions: Determination of the spread of plant infections and the dynamics of infection for the given pathogen. Adaptation of the results to other crops and plant diseases.
4. Monitoring infection levels: Application of remote sensing technologies and methods at different infection stages. Examination of the usability of

technological elements supplemented with the software (GIS) environment. This method can facilitate the precise timing of plant protection interventions or (based on the principles of IPM) promote prevention with effective prognostics.

2. MATERIAL AND METHOD

2.1. Introduction of the experimental area (2021 - 2023)

We established 16 plots in the experimental area of the University of Debrecen. Two fodder and two sweet corn hybrids participated in the study (P9025, ARMAGNAC) (in the case of sweet corn, NOA and DESSERT R73). Artificial downy mildew (Ustilago maydis DC. Corda) infection was carried out with different spore concentrations (spore numbers 2,500, 5,000, 10,000 + uninfected control). The sowing date was the same for all four hybrids in 2021 – April 29, 2021. The sowing was done with a hand-held seed drill, seed by seed in 2021.

The data of the weather and soil condition database were measured and collected by the University of Debrecen's own meteorological station at the experimental site.

The area was kept weed-free during the tests, so the values of the different weed species (VI values) could not influence the values of the tested plots. The rows were kept clean and the use of herbicides was avoided, only mechanical weed control tools were used in this small area.

Experimental area: The plots were of the same size (about 20 m2), with randomized placement. The total size of the experimental area: 400 m2. In the experiment, 3 different levels of infection were carried out on June 3 (in the V5 phenophase). The infectious material used for the experiments was produced by the DE-MÉK NVI staff in all three years (2021, 2022 and 2023) from the institute's goiter Ustilago maydis stock.

- Low dose: 2,500 spores/cm3
- Medium dose: 5,000 spores/cm3
- High dose: 10,000 spores/cm3

The parameters of the multispectral drone I used: 6-camera Multispectral Imaging System (MCS), records 6 images simultaneously on different channels.

- Red Edge (RE): 730 nm ± 16 nm
- Near-Infrared (NIR): 840 nm ± 26 nm
- Green (G): 560 nm ± 16 nm
- Visible Light (RGB)
- Red (R): 650 nm ± 16 nm
- Blue (B): 450 nm ± 16 nm

Source : https://www.dji.com/hu/p4-multispectral

Figure 1: DJI P4M drone

Source: Own photo (Debrecen, 2021)

The experimental setups also took place in Hajdú-Bihar County in the eastern region of Hungary in 2022. The Google Maps GPS coordinates of the experimental site are: (47°33'06.5"N 21°36'07.1"E). The area is part of the experimental garden unit of the University of Debrecen (DE), the demonstration garden of the Plant Protection Institute of the University of Debrecen. We created 24 plots in the area in 2022, which were further developments of the previous year's experiences and results. Based on my previous studies, I selected two different corn hybrids, the Desszert R78 sweet corn and the Pioneer P 9025 fodder corn, which I also used in this study year. These hybrids were more promising for further research based on our previous results. The sowing was done with a GASPARDO 4-row seeder on May 4, 2022. Each plot was set up with four rows, 18.5 cm plant spacing and 75 cm row spacing. The total area was 500 m2. The area between the plots and between the rows was kept weed-free by mechanical weeding until the end of the experiment. No herbicides were used during the research period (we wanted to avoid any yellow-flash effect in the area), so it did not influence the different VI values calculated in the survey stages.

The infection of the goiter (Ustilago maydis [DC]. Corda) was carried out with three different sporidium concentrations on June 3, 2022, using a mass sprinkler. A low spore concentration (spore count) of 5,000 spores/mL was produced, the medium dose was 7,500 spores/mL, and the high dose infection was 10,000 spores/mL. Compared to previous years, the low dose was increased from 2,500 to 5,000 in 2022 and 2023.

Together with uninfected, healthy control plots, 4 treatments were performed, in 3 replicates, each randomized at the test site (Randomized Block Design - RCBD).

The four treatments in the experiment were:
• Uninfected (healthy control).
• Low dose, 5,000 spores/cm3
• Medium dose 7,500 spores/cm3
• High dose, 10,000 spores/cm3

A total of 24 plots were established in the area. Each plot was 24 m2 [Figure 2]. In each case, the artificial infection of the plants was concentrated in the inner parts of the plot. During the UAV image sampling, a multipolygon shapefile (.shp) file was used to extract vegetation index (VI) values from the raster regions. These “sampling boxes/polygons” were each 4.5 m long and 2.5 m wide. Each combined sampling area was concentrated in the interior of the plots.

Figure 2: University of Debrecen research area NVI. DJI Phantom 4 MS multispectral (the image contains all six channels) orthomosaic in QGIS 3.360 environment (2022).
Source: own editing (Debrecen, 2022)

The experimental setups continued in 2023, also in Hajdú-Bihar county, in the eastern region of Hungary. The area is part of the experimental garden unit of the University of Debrecen (DE), the demonstration garden of the Institute of Plant Protection of the University of Debrecen. I created 24 plots in the area in 2023, which were further developments of the previous year's experiences and results. Based on my previous studies, I selected two different corn hybrids, the Desszert R78 sweet corn and the Pioneer P 9025 fodder corn, which I also used in this study, now in its third year. Based on their previous results, the hybrids selected for the study responded better to the bollworm infection. The sweet corn hybrid was the Desszert R78, and the fodder corn hybrid was the Pioneer P 9025. The sowing took place with a GASPARDO brand, 4-row seeder, on April 29, 2023. Each plot was set up with four rows, 18.5 cm plant spacing and 75 cm row spacing. The total area was 500 m2 [Figure 3].

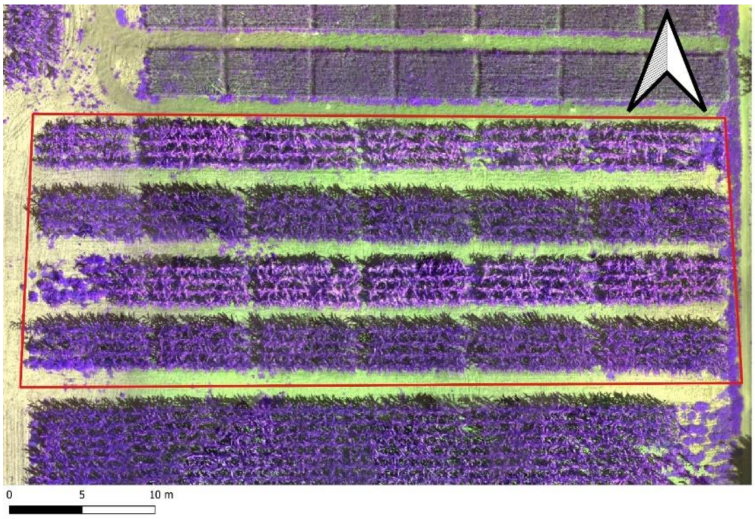

Figure 3: The experimental area in 2023; 24 plots in 4 treatments in 3 replicates; The image contains all 6 channels combined (P4M Ultrahigh (UH) resolution) (2023); The red rectangle indicates the experimental area

Source: own editing (Debrecen, 2023)

The agricultural UAV used in the experiment was a DJI Phantom 4 Multispectral. Data processing and map assembly were also performed using the same methodology as in 2022. I used the WebODM software for the assembly, and the QGIS 3.36 program for the generation of maps and vegetation indices.

Table 1: Vegetation indices and calculation formulas

NDVI	$(R_{NIR}-R_{Red})/(R_{NIR}+R_{Red})$
GNDVI	$(R_{NIR}-R_{Green})/(R_{NIR}+R_{Green})$
NDRE	$(R_{NIR}-R_{RedEdge})/(R_{NIR}+R_{RedEdge})$
LCI	$(R_{NIR}-R_{RedEdge})/ (R_{NIR}+R_{Red})$
ENDVI	$(R_{NIR}+R_{Green}-2xR_{Blue})/ (R_{NIR}+R_{Green}+2xR_{Blue})$

Source: Own editing (Debrecen, 2021)

In 2023, I used five vegetation indices in the studies (Table 1).

1. NDVI (Normalized Difference Vegetation Index),
2. GNDVI (Green Normalized Difference Vegetation Index),
3. ENDVI (Enhanced Normalized Difference Vegetation Index),
4. NDRE (Normalized Difference Red Edge),
5. LCI (Leaf Chlorophyll Index).

2.2. The rating scale for corn smut (*Ustilago maydis*)

The corn smut (Ustilago maydis) can infect various parts of the maize plant. This fungal disease can cause symptoms on all plant parts, including the stem, leaves, ear, and tassel. To objectively assess the extent and severity of the infection, a six-grade rating scale was applied (Table 2).

The evaluation was based on two main criteria:

Proportion of infected plants: How many out of 10 plants were infected.

Severity and extent of infection: Categorized based on the affected plant parts (stem, leaf, ear, tassel).

Categories of infection severity:

- A: Only the leaves are affected.
- B: Symptoms on both leaves and stem.
- C: Symptoms on stem, leaves, and either the ear or tassel.
- D: Symptoms on stem, leaves, ear, and tassel.

Table 2: Rating scale for the severity of corn smut (*Ustilago maydis*) infection

Rating value	**Proportion of infected plants (10/x)**	**Severity of infection (Affected plant parts)**	**Assesment**
1	0/10	No symptoms	Healthy
2	1-3/10	A/B	Minimal infection
3	4-5/10	B	Moderate infection
4	6-7/10	C	Moderately severe infection
5	8-9/10	C	Severe infection
6	10/10	D	Very severe infection

Source: Own editing (Debrecen, 2021)

2.3 The IT softwares

2.3.1. Image stitching - Web ODM (opendronemap.org/webodm)

WebODM is a free application that I used for drone image processing. I created high-resolution orthophotos (in GeoTIFF format) from my own recordings (High. res HR 2 cm/pixel). A total of 6 orthophotos are created at each recording time in different channels (Red, Green, Blue, Near Infra Red (NIR), Red Edge (RE), RGB). DJI's official software DJI TERRA can also be used for further stitching, but this software is licensed, so it requires a subscription. The stitching of the images taken in 2023 was done in the DJI Terra software environment, of course, in addition to the WebODM stitching.

2.3.2. Quantum GIS 3.20 Geospatial software

I used Quantum GIS 3.20 software to create and evaluate the various vegetation index (VI) maps (NDVI, NDRE, GNDVI, LCI, ENDVI). The VI was made in QGIS, as mentioned in the chapter. QGIS has a tool called Shape file creating tool. The Shape.shp files and polygons used were created in it. All vegetation index maps were created with the raster analysis function.

The unit provided in 100% was one of the main aspects of the sampling, so they were duplicated with the Copy and Move element function, which is the (tool used in QGIS). It is part of the extended digitizing toolbox. During the creation of shapefiles (Polygons), 1 polygon was created and then duplicated.

2.4. Statistical analysis methods

I created 16 sampling plots in the shape file layer (in 2021). In 2022 and 2023, there were 24 plots in the areas in 4 treatments, 3 replicates, which were of uniform size. The average values of the zone statistics came from these plots, on which I performed statistical analyses.

I used the statistical analysis supplemented with R 4.1.2. statistical program packages. During all statistical analyses, the set confidence interval for the means was 95% and the Alpha value was 0.05.

I prepared the figures and graphs with Microsoft Excel 2016. Based on the example of (HUZSVAI and BALOGH, 2015), a repeated measures model (Repeated Measures Anova) was used. In 2021, the sampling method was used to investigate the infection and their combined effect on Vegetation Index VI values.

Example of the repeated measures model used for the study in RStudio:

```
model <- aov(Vegetation_Index ~infection +Error (plot_identifier/infection), data = (database) summary(model)
```

The comparison of the mean values was performed using the least significant difference (LSD) method (HUZSVAI and BALOGH, 2015):

```
df=df.residual(model$""parc_az:felvmod")
mse=deviance(model$""parc_az:felvmod")/df
significant_power <- with(database, LSD.test(Vegetation_Index, infection, df, mse, console = T)
```

The figures and graphs were prepared in Jamovi 2.3.28 and MS Excel. I used Jamovi 2.3.28 for the statistical analyses, including descriptive statistics and univariate ANOVA as well. I also used Pearson correlation tests between VIs, which I examined from several aspects (JAMOVI PRJOECT, 2022).

2.5 Measuring instruments used for field measurements.

2.5.1 SPAD 502 relative chlorophyll content meter

The SPAD-502 is a portable chlorophyll measuring instrument (Figure 4), which is mainly used for agricultural, plant physiology, plant stress, nitrogen supply, and yield estimation in both economic and research environments. The instrument can perform non-destructive measurements on plant foliage. The instrument is manufactured by Konica Minolta. The measurement principle is based on transmittance, measuring the amount of light absorption in the 650-nm red range and the 940nm NIR range, and based on this, the instrument calculates a so-called SPAD value, which shows a strong correlation with plant chlorophyll content.

The instrument is small in size, making it portable and easy to use for measurements in field conditions. The SPAD value ranges from 0-99.9. The measurement time is It takes approximately 2-3 seconds and displays the measurement values on the device's LCD display. The SPAD 502 is a reliable measuring instrument and is widely used by researchers.

Figure 4 : SPAD-502 relative chlorophyll content measuring instrument

Source: https://www.kosmos.com.mx/tienda/catalog/images/thumbs/801_600/SPAD-502-Demo.jpg

2.5.2 Trimble GreenSeeker NDVI instrument

The Trimble GS instrument is based on remote sensing technology. Using this, we are able to record NDVI values in the field. The GS NDVI values can be widely used for crop estimation models, as well as for plant stress diagnostics and evaluation of its extent. The device calculates the Normalized Difference Vegetation Index (VI) values. The measurement spectrum of the instrument is 660 nm in the Red light range and 780 nm in the Near Infrared light range (NIR). The measurement distance can also vary depending on the size of the vegetation, but usually ranges from 60 cm to 200 cm.

3. RESULTS

The VIS-SWIR remote sensing technology method is based on the diverse spectral response of plants to different stress factors. The water content, cell structure, and pigment content ratio of plants affected by various diseases change significantly. The images collected by multispectral UAVs and the vegetation indices calculated from them play a critical role in identifying plant diseases, determining the severity of the infection, and assessing plant photosynthetic activity and stress status. In the 2021 experimental year, I examined four different corn hybrids: two fodder corn hybrids (Pioneer P 9025 and Armagnac), two sweet corn hybrids (Desszert R73 and NOA). In the case of the sweet corn hybrid examined, previous studies also confirmed that after 11 DAI (11 days after artificial bollworm infection), the concentration of photosynthetic pigments in plants decreased significantly (SZŐKE et al., 2021).

Based on my 2021 and later study results, I found that GNDVI can be used for such purposes, including corn rootworm.

In my own experiments, the LCI values for the Desszert R 73 hybrid were able to reflect the effect of the corn rootworm Ustilago maydis [DC.] Corda. The plots treated with the highest CS 10,000 spore concentration showed significantly lower VI values than the control CS 0.

In the case of the Desszert R73 hybrid, statistical tests showed that infection levels have an effect on the change in vegetation index values for all three vegetation indices (Table 3).

Table 3: Vegetation index values for the Dessert R73 RMA model

Infection	Df	Sum Sq	Mean diff	F value	Pr(>F)
LCI	3	0,0030246	0,0010082	21,059	0,00138 **
NDVI	3	0,003874	0,0012913	7,927	0,0165 *
GNDVI	3	0,010228	0,003409	15,61	0,00307**

Source: own editing (Debrecen, 2021)

I also found that the infection reduced the values of the vegetation indices in proportion to the increasing spore concentration. I surveyed the area at three different times: 7 days, 14 days and 21 days after infection.
In the case of the Desszert R73 hybrid, three different VIs showed that the canker infection significantly influenced the calculated values, in the case of the GNDVI, NDVI and LCI indices. Based on my test results, I found that these three vegetation indices can be used well in assessing the disease. In the case of the NOA sweet corn hybrid, two VIs showed well the effect of the corn canker infection (GNDVI, ENDVI).
A new finding of my studies was that according to the results obtained, the GNDVI provided an outstanding result in the case of Ustilago maydis [DC.] Corda disease monitoring. It was also shown that the infection significantly influenced the measured values in the case of the two sweet corn hybrids (NOA and Desszert R 73). NDVI, LCI and ENDVI also showed excellent results for detecting changes caused by the pathogen Ustilago maydis. The modified RMA model was able to detect the change in the different VI values during the infection period. By increasing the spore concentration, the values became lower in the plots treated with the pathogenic fungus and the dynamics of the infection were also clearly shown. With the survey and sample collection method used in the experiment, the sample values of the VIs can be objectively analyzed and evaluated, and can be easily adapted to other plant crops. The results showed that the dynamics of the values changed over time. Field validation is still necessary in all cases, and the values of the severity scales should be determined depending on the crop, after the evaluation. The experimental sites or the affected agricultural areas can be observed at an appropriate level and quality with the multispectral devices currently available on the market.

My conclusions based on the SPAD and GS NDVI values are as follows:
I conducted statistical tests and the correlations between the parameters separately in all 4 tested hybrids. Since SPAD is a widely researched parameter, especially in the development of models estimating nitrogen management and yield growth. In the case of the tested hybrids, the SPAD value showed a continuous increase in almost all cases at each time point, which is closely related to the relative chlorophyll content and GS NDVI values. The recording times had a significant effect on the recorded values. Furthermore, GS NDVI is also a widely used yield estimation parameter in other models (ARANGUREN et al. 2020.). A very strong positive correlation could be demonstrated between GS NDVI and SPAD values (based on the results of 2021) in almost all cases,

in line with the findings of ZSEBŐ et al. in 2024. The 4th-5th recording time already mitigated this phenomenon, however, the GS NDVI values were greatly influenced by the period of crest vomiting. GS NDVI and SPAD values are predictors of each other during optimal weather and growing periods (Figure 5).

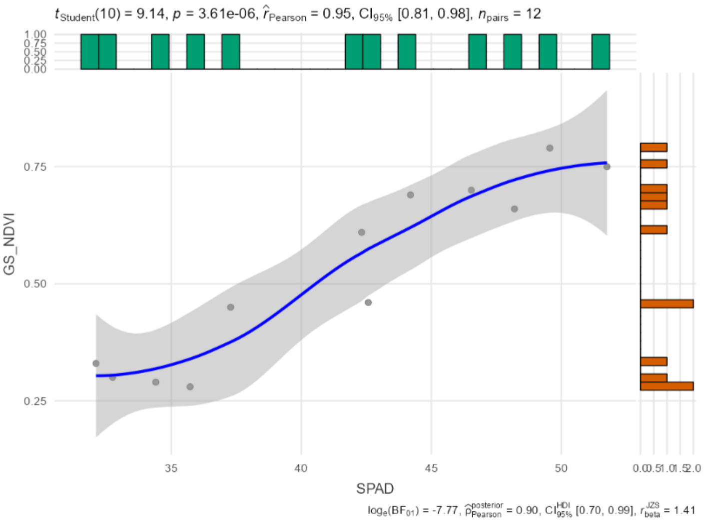

Figure 5: GS NDVI-SPAD Correlation results for the Dessert R73 Hybrid at monitoring date 1-3 (2021)

Note: The correlation analysis results contain data from monitoring date 1-3.

Source: Own editing (Debrecen, 2021)

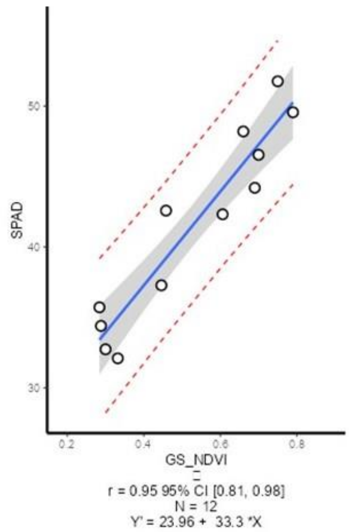

Figure 6: Correlation between SPAD and GS NDVI Parameters for the Dessert R73 Hybrid

*Note: The X-axis represents GS_NDVI predictor values, the Y-axis represents SPAD predictor values. LRE: Y’ = 23.96 + 33.3*X.*

Source: Own editing (Debrecen, 2021)

There was a very strong positive correlation between the SPAD and GS NDVI values, with the correlation coefficient (CCoe) value [$r = 0.95$] and the statistical significance p-value of $p = 3.06 \times 10^{-6}$. The confidence interval (CI) range is [0.81, 0.98]. Furthermore, due to the strong relationship between the two parameters, they can be widely applied in the integration of predictor models. The calculated linear regression equation (Figure 6) is $Y' = 23.96 + 33.3*X$, which means that a 0.15 unit increase in GS NDVI value induces a 4.995 increase in SPAD value.

My experiments continued in 2022. This year, only two hybrids participated in the studies. The sweet corn hybrid was Desszert R78 (CS hybrid) and the fodder corn hybrid was Pioneer P9025 (T hybrid). I examined the reactions of the hybrids to artificial bollworm infection using a multispectral UAV. In the case of the Desszert R78 hybrid, the symptoms developed normally and were clearly visible in the infected areas. During the data analysis, I found that the NDVI values of the CS 0 (healthy) control plot showed a significant difference compared to the three infection levels (CS 5,000, CS 7,500, CS 10,000). ZHAO et al. (2020) also used NDVI indices (vegetation index normalization) to identify the severity levels of plant diseases.
The results of GNDVI in 2023 were encouraging, but in 2022 only one difference could be statistically proven between the CS 0 and CS 7,500 values. However, GNDVI is an extremely useful tool for identifying and evaluating the severity levels of plant diseases. In terms of experimental results, I did not experience major differences in the values of the fodder maize hybrid. All VI values of the hybrid P9025 (based on the results of 2022) were relatively identical and showed an even spatial distribution. The different treatments did not have a significant effect on the calculated vegetation index values. The vegetation in the area was vital and uniform. However, in my experimental area, I demonstrated that the separation of hybrid types based on the vegetation index values is reliably possible. Both NDVI and ENDVI gave adequate results for comparing the values of the hybrids (Table 4).

Table 4: Comparison of NDVI values of the examined hybrids (Analysis of variance) Desszert R78 and P9025. (2022)

		CS 0	CS 5.000	CS 7.500	CS 10.000
T 10.000	mean diff	0,02002	0,05177**	0,059467***	0,07423***
	p-value	0,771	0,00537	$9{,}11 \times 10^{-4}$	$2{,}47 \times 10^{-5}$
T 5.000	mean diff	0,02247	0,05422**	0,061917***	0,07668***
	p-value	0,655	0,00309	$5{,}07 \times 10^{-4}$	$1{,}34 \times 10^{-4}$
T 7.500	mean diff	0,01865	0,0504**	0,0581**	0,07287***
	p-value	0,827	0,00727	0,00126	$3{,}47 \times 10^{-5}$
T 0	mean diff	0,03528	0,06703***	0,074733***	0,0895***
	p-value	0,138	$1{,}47 \times 10^{-4}$	$2{,}18 \times 10^{-5}$	$5{,}48 \times 10^{-7}$
Note. * p < .05, ** p < .01, *** p < .001					

Source: own editing (Debrecen, 2022)

The identification and differentiation of hybrids based on UAV-based imagery data is a widely researched area. For example, SANTANA et al. (2024) used multispectral imagery (combined with machine learning [ML]-based techniques) to identify sorghum hybrids. In this study, multispectral imagery played a prominent role. The high correlations between vegetation indices also gave encouraging results in my own studies. In the case of GNDVI and NDVI, r = 0.83, and in the case of LCI and NDRE, r = 0.973. NJANE et. al. (2023) also obtained similar correlation results regarding the index analysis. In conclusion, NDVI and similar vegetation indices provide a suitable basis for technological applications based on new methods. In the case of the two hybrids examined in 2022, SPAD and GS NDVI values were also recorded and analyzed. The year 2022 was a very dry and rainy year, especially in Hajdú-Bihar. The recorded values showed obvious anomalies due to extreme climatic factors. The recording time had a significant effect on the SPAD and GS NDVI values for both hybrids. The treatments did not show any effect on the measured parameters. Several researchers also observed a moderate positive correlation between the parameters. But negative correlation also occurred in many cases (YIN et. al., 2023). Soil moisture, lack of precipitation, and extreme heat negatively affect the correlation between the parameters. Based on the results of 2022, there was a negative correlation between the SPAD and GSNDVI parameters in several cases.

In 2023, I continued my investigations, building on the experiences and results of the previous two experimental years. During the 2023 studies, I also performed 4 treatments (uninfected control, low dose 5,000 spores/cm3, medium dose 7,500 spores/cm3; high dose 10,000 spores/cm3), in 3 repetitions. Thus, a total of 24 plots were established. In the experiments (similar to 2022), the sweet corn hybrid was Desszert R78, and the fodder corn hybrid was Pioneer P9025. In the study, I calculated five vegetation indices: NDVI, GNDVI, NDRE, LCI and ENDVI. Of the vegetation indices examined, NDVI gave appropriate results for the sweet corn hybrid. The values of the CS 0 plot were significantly different from all three infection levels, so the difference in the means could be statistically verified. In addition to NDVI, GNDVI also showed adequate results for detecting differences between infection levels. Based on these results, the NDVI and GNDVI indices proved to be stable for tracking changes caused by the pathogen even in the 3rd year.

Regarding the SPAD and GS NDVI values of 2023, a decrease in SPAD values was observed in the Desszert R78 hybrid at each time point. The measurement times also showed a statistically verifiable effect, both for SPAD and GS NDVI values. Correlation studies showed a moderate positive correlation between the measured parameters in many cases. The correlation relationship between the parameters is mostly high and under optimal conditions (if there is a very strong positive relationship) they can also be predictors of each other.

The main goal of my research was to monitor the detectability of plant pathogens and their territorial spread using sensor measurements. The studies were conducted over three years and I used isolates of the corn smut pathogen Ustilago maydis [DC. Corda] to carry out artificial infections. Plant pests cause significant qualitative and quantitative damage to the crop every year. The extensive and accurate spatial data collection provided by VIS-SWIR remote sensing technology can be a new basis for sustainable and precision agricultural practice. In the research, I used a DJI Phantom 4 Multispectral agricultural UAV, which provided high-quality and sufficiently detailed data maps of the studied areas. I identified 4 main directions in the objectives of my research:

1. Detailed examination of the spectral properties of infected and healthy plant populations based on multispectral images.

2. Proper processing of the data and examination of the use of data analysis for plant protection purposes.

3. Identification of data distributions and deviations in them in the field and development of the correct methodological method.
4. Furthermore, a very important element of my research was the examination of the applicability of the technology for identifying early or already established infections and for monitoring the developmental dynamics of the disease process.
In addition, I also performed sensor measurements to record and examine SPAD and GS NDVI values.
My goal was to show the changes caused by artificial infections with different spore concentrations in the values of the vegetation indices, as well as to select the vegetation indices most suitable for identifying problems.

The year 2021 was the first year of the experiments, when I examined two fodder corn hybrids (Pioneer P9025, Armagnac) and two sweet corn hybrids (NOA, Desszert R73). Based on the results of the first year, I identified the dynamic change between the infection levels and the changes in the vegetation index values induced by the infection using a unique RMA model. In 2021, I also managed to identify three vegetation indices that may be suitable for achieving the set study goals. Based on the results of 2021, in the case of the examined sweet corn hybrid Desszert R73, LCI, NDVI and GNDVI could be successfully applied to the data sets measured in that year.

In the following years, my research was aimed at a more detailed mapping of the relationships between the severity of the infection and the vegetation indices. In the case of sweet corn and fodder corn, I used hybrids that showed appropriate plant physiological reactions in the previous year with four treatments and three repetitions. The analysis of variance studies showed convincing results to confirm the negative changes in VI values caused by the infection, especially in the case of sweet corn (Desszert R78 hybrid). The use of the NDVI and GNDVI indices proved to be suitable for achieving the experimental goals in the second experimental year.

Then I used correlation studies and the examination of spatial data distributions to detect more detailed connections between the vegetation indices. In many cases, these showed overlap with the results of research found in the international literature, which further strengthened the usability of the results achieved in my own research. During the studies of SPAD and GS NDVI values, several important factors were confirmed and new relationships were mapped. I found that in all cases the recording times have an effect on SPAD and GS NDVI values. The treatments showed less statistically verifiable effects on the measured values. There is a strong positive correlation between the two parameters under optimal conditions, thus they can be predictors of each other and can be well-suited parameters in different predictor models. The vintage effect greatly influences the correlation values between GS NDVI and SPAD. Hybrid separation studies (also based on variance analysis) of sweet corn They were based on the separation of the VI values of Desszert R78 and Pionner P9025. In the case of hybrids, NDVI and ENDVI showed adequate usability for this type of separation. In the 2023 experimental year, the hybrids used in the previous year were also sown, with similar settings and number of repetitions. Multispectral UAV data collected in the third year further confirmed the results obtained in the previous year. The NDVI values decreased further this year with the increase in infection doses, and a significant difference in the averages could also be verified in the case of GNDVI. The values of the plants in the plots of sweet corn hybrids treated with the highest spore dose showed a particularly large decrease. In the case of fodder corn hybrids (P9025), the same findings as in previous years were also made. Based on these, the symptoms, if they developed on the infected plots, did not cause serious growth retardation or tissue damage in the fodder corn stands. Based on my research results, it can be concluded that VIS-SWIR remote sensing technology is an effective system for identifying corn stem borer [Ustilago maydis [DC] Corda] infection and estimating its expected damage.

Despite the fact that drone monitoring technology appeared in Hungary a few years ago, spectral characteristics and their examination in European agriculture have a history of more than ten years. The mass appearance of these devices and their increasingly simplified "user-friendly" applications also help in precision agricultural applications and their use for plant protection purposes.

4. NEW SCIENTIFIC RESULTS

1. Based on the results of the years of study, I determined that three vegetation indices may be suitable for the identification of corn leaf blight [*Ustilago maydis* [DC.] Corda]. These are LCI, NDVI and GNDVI.
2. I determined that both NDVI and ENDVI indices are suitable for the separation of corn hybrids (forage and delicacy) based on VI data in the studied areas.

3. Based on the results of my correlation analysis, I determined that the selection of additional vegetation indices (VIs) and their application for monitoring specific plant diseases is possible. The correlation coefficients (CCoe) were as follows: GNDVI-NDVI CCoe [r = 0.83], LCI-NDRE CCoe [r = 0.97], NDRE-GNDVI CCoe [r = 0.716]. The results obtained here could contribute to the development of advanced plant-specific algorithms or the further development of individual VIs, which could be disease-specific.

4. The infection of corn smut (*Ustilago maydis* [DC.] Corda) significantly reduces the average values of vegetation indices (NDVI reduces by 20-50%, GNDVI reduces by 25-45%, LCI reduces by 30-40%) with increasing spore concentration (spores/mL) (up to 10,000) in sweet corn Dessert R73 and Dessert R78 populations.

5. The SPAD and GS NDVI parameters (under optimal weather conditions) are predictors of each other, making them highly applicable for the development of estimation models. $Y' = 23.96 + 33.3*X$, meaning that a 0.15 unit increase in GS NDVI results in a 4.995 increase in SPAD units. In the Dessert R73 hybrid (2021), the correlation coefficient (CCoe) was [r = 0.95].

6. The SPAD and GS NDVI values are greatly influenced by the acquisition time and the climatic factors of the growing season. In extreme weather conditions (severe drought stress), a negative correlation can be observed between the parameters. For Dessert R78 (2022), the correlation coefficient (CCoe) was [r = -0.17].

5. RESULTS THAT CAN BE USED IN PRACTICE

1. After the complete data filtering and data cleaning process, a more detailed exploration of spatial differences can be performed in GIS systems.

2. The use of NDVI, GNDVI, ENDVI, and LCI vegetation indices is also suitable for identifying other diseases. It is possible to adapt the methodology to other crop crops.

3. Accurate and detailed plant health assessment of sweet corn stands can be successfully implemented using VIs.

4. The use of technical and flight parameters, which, based on the results of this study, allow for more precise settings and better quality multispectral images.

5. The examination of GS NDVI values is recommended only during optimal recording periods.

6. The recording of SPAD values is possible in the appropriate phenological phase (precise time selection).

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PUBLICATIONS ON THE TOPIC OF THE THESIS

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Candidate: László Radócz
Doctoral School: Kálmán Kerpely Doctoral School
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List of publications related to the dissertation

Foreign language scientific articles in Hungarian journals (1)

1. **Radócz, L.**, Sápi, L., Zagyi, P., Horváth, É., Tamás, A.: Analysis of the plant physiological effects of late, artificial corn smut infestation using remote sensing methods.
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