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ASSESSMENT OF THE SUITABILITY OF SPECTRAL INDICES FOR DETECTING AREAS OF INCREASED STRESS AMONG PLANTS – A CASE STUDY OF THE BOTANICAL GARDEN IN KIELCE

OCENA PRZYDATNOŚCI WSKAŹNIKÓW SPEKTRALNYCH DO WYKRYWANIA OBSZARÓW WZMOŻONEGO STRESU WŚRÓD ROŚLIN – STUDIUM PRZYPADKU OGRODU BOTANICZNEGO W KIELCACH

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Abstract

An important factor threatening global security is climate change and its impact on changing rainfall patterns and seasonal temperature variability. For this reason, farmers and crop scientists are striving to detect plant stress as soon as possible and introduce preventive measures so that key decisions in maintaining plant health are made in a timely way. Currently, multispectral images acquired from UAVs (Unmanned Aerial Vehicles) make it possible to provide objective and reliable information related to the state of agro-ecosystems, the dynamics of changes occurring on them and the monitoring of natural resources in a rapid and non-contact method. In the present study, the suitability of low-altitude multispectral imaging for proper stress detection in plants was assessed. The botanical garden in Kielce, a site with a high biodiversity of plant specimens, was chosen as the testing ground. In this study, four spectral indexes maps were analysed in the form of: NDVI (Normalized Difference Vegetation Index), NDRE (Normalized Difference Red-Edge Index), GNDVI (Green Normalized Difference Vegetation Index) and the less frequently used PSRI (Plant Senescence Reflectance Index) for the assessment of plant health. PSRI values > 0.50 clearly identified areas of high stress, in contrast to the other spectral indices analysed in this study. The study confirmed the suitability of the PSRI for conducting monitoring activities in areas with varying crop characteristics in an efficient and rapid approach.

Keywords: Remote Sensing (RS), botanical garden, crop monitoring, stress detection, Plant Senescence Reflectance Index (PSRI), Unmanned Aerial Vehicle (UAV), Precision Agriculture (PA)

Streszczenie

Ważnym czynnikiem zagrażającym globalnemu bezpieczeństwu są zmiany klimatyczne i ich wpływ na zmiany wzorców opadowych oraz zmienność sezonowych temperatur. Z tego powodu osoby zajmujące się ochroną walorów przyrodniczych oraz upraw dążą do jak najszybszej detekcji stresu roślin i wprowadzeniu działań profilaktycznych, aby kluczowe decyzje w utrzymaniu zdrowia roślin zostały podjęte w odpowiednim czasie. Obecnie zdjęcia multispektralne pozyskane z UAV (ang. Unmanned Aerial Vehicles) umożliwiają dostarczenie obiektywnej i wiarygodnej informacji związanej ze

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stanem agrosystemów, dynamiki zmian na nich zachodzących oraz monitorowania zasobów przyrodniczych w sposób szybki i bezkontaktowy. W niniejszej pracy oceniono przydatność zobrazowań multispektralnych z niskiego pułapu do prawidłowej detekcji stresu u roślin. Jako poligon doświadczalny wybrano ogród botaniczny w Kielcach, będący obiektem o dużej bioróżnorodności okazów roślin. W pracy przeanalizowano cztery mapy wskaźników spektralnych w postaci: NDVI (ang. Normalized Difference Vegetation Index), NDRE (ang. Normalized Difference Red-Edge Index), GNDVI (ang. Green Normalized Difference Vegetation Index) oraz rzadziej stosowany wskaźnik PSRI (ang. Plant Senescence Reflectance Index) pod kątem oceny kondycji zdrowotnej roślin. Wartości wskaźnika PSRI > 0,50 w sposób jednoznaczny zidentyfikowały obszary wysokiego stresu w odróżnieniu od pozostałych analizowanych w pracy wskaźników spektralnych. Badania potwierdziły przydatność wskaźnika PSRI do prowadzenia działań monitoringowych na obszarach o zróżnicowanej charakterystyce uprawianych roślin w sposób efektywny i szybki.

Słowa kluczowe: teledekcja, ogród botaniczny, monitoring upraw, detekcja stresu, wskaźnik spektralny PSRI, bezzałogowy statek powietrzny (BSP), rolnictwo precyzyjne

1. INTRODUCTION

Historically, plant diseases were monitored visually by people who had expertise in this area of science. Observations of plant phenology carried out in this way were subject to bias and observer error, which contributed to the search for an alternative technique for monitoring plant health [1]. Currently, multispectral imagery acquired from UAVs makes it possible to provide objective and reliable information related to the condition of the agro-ecosystem, the dynamics of changes occurring on them and the monitoring of natural resources in a rapid and non-contact manner [2-4]. Conducting monitoring activities in botanical garden areas through the implementation of unmanned aerial vehicle technology, allows not only a rapid response to local anomalies (e.g. in the form of waterlogging, drought, increased pest activity) but also the estimation of yield capacity and maintenance of plants in good health [5]. Unfortunately, many scientific papers focus on the use of multispectral UAV imagery for specific crops and thus fail to test the versatility of this technology for a wider range of plant species.

Monitoring activities to assess plant growth and condition have been carried out for many years using imagery that captures infrared radiation [6]. Remote sensing provides objective documentation, and the scale, resolution and nature of the imaging can be tailored to the specifications of the task at hand [7]. Thanks to the miniaturisation of aerial cameras and thus their increased availability, remote sensing methods for environmental monitoring have found a number of applications in the life sciences. Unmanned aerial vehicles enable the adaptation of compact sensors (e.g. multi- and hyperspectral cameras), making it possible to carry out cyclic low-altitude flights with greater safety than manned aircraft, thereby increasing the spatial resolution of the images [1, 6, 8]. Satellite platforms with mounted remote sensing sensors can be an alternative. However, they have some limitations for monitoring plant physiology. The main limitations are the large Ground Sampling Distance (GSD), insufficient revisit time during the growing season and sensitivity to meteorological conditions (cloud cover). In addition, the low spatial resolution of satellite imagery (e.g. MODIS satellite, Landsat 7 and 8) translates into the 'mixed pixels' phenomenon and degrades the spectral purity of the samples under study, which in turn affects the outcome of the quantitative and qualitative analyses. For this reason, images acquired by UAVs appear to be the right direction for the acquisition of spatial information on plant vegetation in a rapid and less weather-dependent manner.

The main objective of the research presented in this paper was to assess the suitability of low-altitude multispectral imaging acquired with the Micasense Red-Edge MX camera for the successful detection of stress in plants. The indirect aim of the experiments carried out was to determine the potential of the NDVI, NDRE, GNDVI spectral indices, and in particular the PSRI index, for the rapid identification of anomalies within the analysed experimental facility, which was the botanical garden in Kielce (Poland).

2. LITERATURE REVIEW

Many European gardens were established as facilities for growing medicinal plants and are often an integral part of Europe's cultural heritage. The current purpose of botanical gardens is most often to protect plant diversity. According to data presented in the paper [9], at least 20% of currently existing plant species are threatened with extinction. This can have implications for human innovation when trying to meet challenges such as food security and biodiversity conservation. Rational land management requires

environment

reliable information on land cover, land use and changes occurring [10]. Information provided from a number of sources [3, 11-13] highlights that photogrammetry and low-altitude remote sensing data can be useful for a better understanding of soil processes and plant assimilation apparatuses, which in turn can translate into more effective crop management.

A significant factor threatening global security on many levels is climate change and its impact on changes in precipitation patterns and seasonal temperature variability. For this reason, conservationists aim to detect plant stress as soon as possible and introduce preventive measures so that key decisions in maintaining plant health are made in a timely manner [14]. Phenological observations are classically carried out for specific plant species in botanical gardens, small research areas or agricultural fields around the world and date back to the 19th century [15]. Although these observations are of interest for studying trends in phenology over time and their causal factors, they are often spotty and therefore provide only little information on spatial variability. In this context, low-altitude remote sensing data can provide valuable information on phenology and enable dynamic mapping of vegetation development and monitoring of their stress conditions, i.e. the response of plants to unfavourable environmental conditions. UAV imagery – and in particular multispectral imagery and the spectral indices calculated from it – has been used repeatedly by other researchers to detect symptoms of plant impairment due to biotic and abiotic factors [1, 5]. Spectral indices are a set of ratios and mathematical transformations of the reflectance intensity recorded by a detector in different spectral channels. Many spectral indices are calculated from spectral channels registering the red and infrared bands because of the high correlation between the contrast in absorption of these bands and the health of the plant group analysed. This approach, thanks to its efficiency, has found wide application in the natural sciences, relating the values of spectral indices to the physical phenomena or physico-chemical parameters with which they correlate [16, 17].

A literature review [5, 14, 16, 18, 19] repeatedly highlighted the usefulness of remote sensing techniques for conducting effective monitoring of plant health and locating pest sites in growing areas. The authors' results [20] indicated an increase in pest abundance with a decrease in the NDVI index in both variants of the analyses conducted, i.e. using data from an aircraft and CIR composition and a satellite recording spectral reflectance in multiple channels. Thus, the relationship between Hessian fly occurrence and the normalised difference vegetation index (NDVI) in winter wheat fields in Kansas (USA) was confirmed. This means that only the cooperation of remote-sensing specialists with biologists, allows the values of the obtained spectral indices to be correctly interpreted and the cause determining the reduced plant health to be known.

According to [17], remote sensing data can be used to detect and monitor plant species diversity. In their study, the authors highlighted that plant diversity (mono-cultural and multi-species) has a close relationship with remote sensing metrics and their productivity. Thus, the monitoring of flora-diverse areas should be considered individually for the plant species under study.

The development trend of plants depends on many conditions, including the occurrence of biotic and abiotic factors that negatively affect vegetation. Capturing the timing of groups of such factors based on in situ ground measurements is dependent on the plantation area. According to [11, 21], more and more plant care professionals are using drones to provide preventive measures in the aforementioned area. In this way, it is possible to reduce the potential risk of stressors among plants in areas with a large surface area and, as a result, to ensure the correct course of vegetation of plants at the most important moments of their development stage [3, 5].

The main role of UAVs in monitoring plant phenology is to acquire multispectral images that, when processed, enable the identification of hotspots (e.g. the presence of pests or insects) and regions at increased risk of drought or waterlogging. Furthermore, spatial and multitemporal maps of spectral indices allow observations of the effects of applied nitrogen fertilisers and pesticides on vegetation development [16]. It is worth mentioning that in some scientific papers [1, 17], the authors identify low-altitude remote sensing as an information acquisition technique for the construction of predictive models of plant condition based on artificial intelligence. This approach makes it possible to increase the precision of plant disease identification and monitoring at an early stage, which seems a good research direction.

Digital documentation of botanical gardens is important not only for maintenance work, but also for the proper management of the site and the provision of tourist and educational services. The diverse landscape forms and variety of nurtured plants within a botanic garden, translate into the uniqueness of such creations on a national scale [22, 23]. Given the complex layout of botanic gardens and the diverse flora, modern surveying technologies may prove to be an appropriate form of recording and then processing and sharing the information available in botanic gardens through GIS [18, 24].

All the monitoring activities and examples presented earlier, create UAV technology as a rich support tool during the management of a botanic garden, thus influencing relevant decisions and policies for the management of the site.

3. METHODOLOGY

The work involved in the measurement experiment was divided into four main stages:

1. Selection of a representative testing area.
2. Establishment of a photogrammetric network and acquisition of UAV images with an adapted optical and multispectral camera, at two different vegetation periods.
3. Performing optical and multispectral orthomosaics for two time periods and calculating NDVI, NDRE, GNDVI and PSRI spectral indexes maps on their basis.
4. Field verification of the results obtained and assessment of the suitability of the selected spectral indices for the study.

The workflow adopted was to evaluate low-altitude remote sensing technology for conducting analyses based on spectral indices for a wide range of plants. Compared to thematically similar studies in the field of remote sensing environmental monitoring, an innovation in the presented methodology is the implementation of the rarely used spectral index PSRI to assess the condition of a wide range of plant species. The following chapters describe in detail the stages of the experimental fieldwork and computational work.

3.1. Selection of the test object

The object of the research was a botanical garden with an area of approximately 11 hectares and located in the city of Kielce, the capital of the Świętokrzyskie Voivodeship in Poland. The detailed location of the study object is shown in Figure 1.

The garden is located on the slopes of the Karczówka mountain from where one can observe the panorama of the city of Kielce and the nearby ranges of the Świętokrzyskie Mountains (Geonatura Kielce – Botanical Garden Website, access: 20.11.2022). The area of the botanical garden is diverse in terms of biodiversity and topography. The height differences within the garden reach 20 metres, while the terrain slopes towards the south.

The botanical garden complex in Kielce comprises eight main sectors, with further plant collections including:

- Ornamental plants section – peonies, lilies, hydrangeas, roses, ornamental grasses;
- Section of useful plants – medicinal and spice plants, orchard plants, vineyard, flower meadow;
- Native flora section – upland mixed fir woodland, sub-continental oak-hornbeam, light oak, heathland;
- Water and marsh flora section – water lilies, native water and marsh plants, water scythes;
- Demonstration garden section – French, country, oriental and Japanese gardens.

There were two main reasons for choosing the site presented for the study. Firstly, the botanical garden was considered to be a representative example of a large diversity of plant species contained within a small area. The second reason was that there was a history of repeated disease of some of the plant specimens, including: the roses and azaleas collection (over 15 acres), the heathland (approximately 20 acres) and the East Asian woodland collection (approximately 10 acres). The advice of the garden personnel on how to verify the observations made was an added advantage of the chosen research site. Thus, the research discussed in the publication was practical and the results obtained could be implemented to improve the functioning of the site presented in the paper and to better understand the phenology of the existing plants in the garden.

3.2. Description of study

The measurement experiment was planned during the vegetation period of plants located on the grounds of the botanical garden in Kielce. Two flights by unmanned aerial vehicle were carried out on 24.05.2022 and 13.07.2022, with variable weather conditions (variable cloud cover and wind direction) during each measurement day. In each measurement series, an X5S optical camera (15 mm focal length) and a Micasense Red-Edge MX multispectral camera were attached to the drone. The execution of the two UAV flights at different times was intended to assess the trend of plant development and to select a more favourable period of plant phenology for subsequent studies using flying measurement platforms and analyses based on spectral indices. A detailed diagram of the work carried out for the two UAV flights carried out is presented in Figure 2.

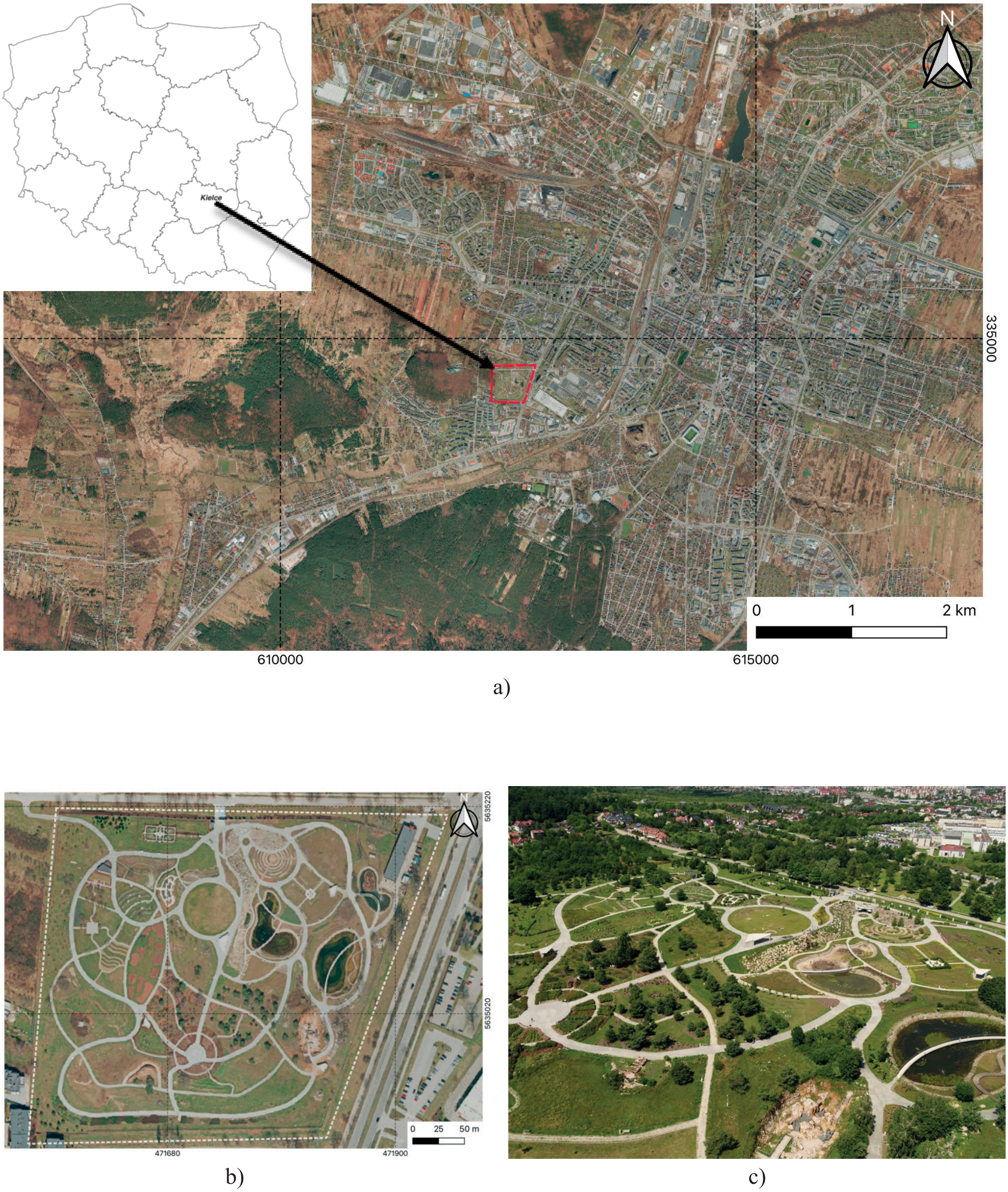


Fig. 1. Location of the botanic garden in Kielce: a) location of the research object in Poland (coordinates in the Polish small-scale development system, EPSG: 2180), b) top view of the botanic garden, c) view of the garden in the north-western direction

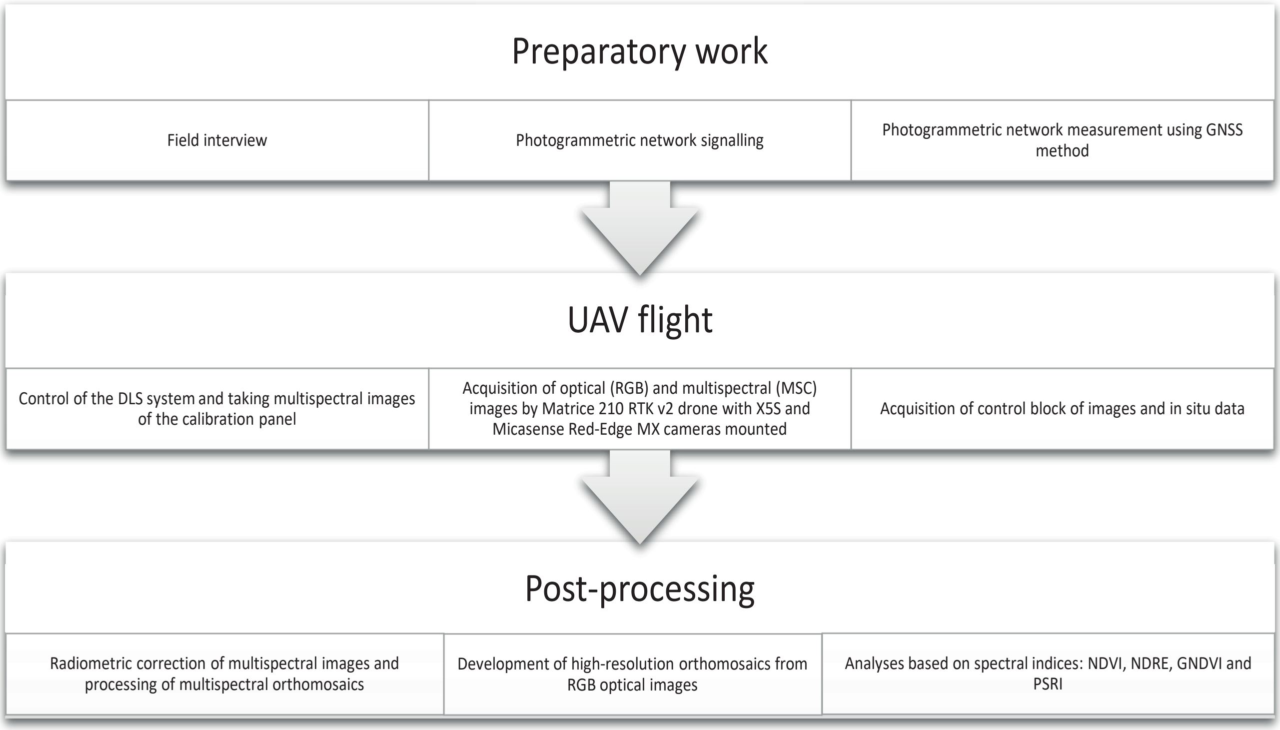


Fig. 2. The workflow used in the study

3.3. Field work

The work began with a field interview to identify field details that act as a natural photogrammetric network for the absolute orientation of the images. The survey network was necessary to ensure high geometric accuracy of the final products of the image processing and, as a result, to enable reliable comparative analyses from the two measurement periods. The terrain details, which are usually kerbstones or manhole covers, were measured using GNSS (Global Navigation Satellite System) technology. For this purpose, a Topcon HiPer HR satellite receiver was used, operating with reference to the TPI NETpro reference station network. A total of 16 points were measured as ground control points and check points. The accuracy of the spatial coordinates of the measured points was $mp_{XYZ} < 3$ cm.

The aerial missions were carried out using a Matrice 210 RTK v2 unmanned aircraft (Fig. 3), which allows adaptation and operation with two optical sensors simultaneously. The a'priori parameters of the photogrammetric flight were the same for both time periods analysed (May and July). The projected field pixel was 1.8 cm/pix for the X5S optical camera and 5.7 cm/pix for the multispectral camera. The overlap and cross-sectional coverage images were 70%, respectively, which is in line with the experience of other researchers carrying out UAV missions for surface mapping [6, 26]. In addition, the flight of the UAV was signalled to the spatial information services through the teleinformation system recommended by the Polish Air Navigation Services Agency (PANSA).

Fig. 3. Matrice 210 RTK v2 unmanned aerial vehicle used in the study, with the Micasense multispectral camera (left side) and X5S optical camera (right side) and DLS sensor (top of the drone) mounted

Table 1 presents the specifications of the Micasense Red-Edge MX five-channel multispectral camera used in the study. Before the UAV flight and after the UAV mission, images of the calibration panel were acquired. Due to variable cloud cover during both survey days (24.05.2022 and 13.07.2022), ambient irradiance information was additionally recorded via the Downwelling Light Sensor (DLS) so that the results from the radiometric correction performed would be more accurate.

Table 1. Micasense Red-Edge MX multispectral camera specifications

Weight	231.9 g	
Spectral Bands	Blue, Green, Red, Red edge, Near-IR, 12-bit RAW for each	
Dimensions	8.7 cm x 5.9 cm x 4.5 cm	
Wavelenght (nm)	Band 1	Blue – 475 nm center, 32 nm bandwidth
	Band 2	Green – 560 nm center, 27 nm bandwidth
	Band 3	Red – 668 nm center, 14 nm bandwidth
	Band 4	Red edge – 717 nm center, 12 nm bandwidth
	Band 5	Near-IR – 842 nm center, 57 nm bandwidth
Ground Sample Distance (GSD)	8 cm per pixel (per band) at 120 m AGL	

Source: Micasense Producer Website, access: 20.11.2022.

3.4. Control measurements

In order to control the results obtained from the analyses based on spectral indices, an additional block of multispectral images was acquired for each time period. In total, four blocks of multispectral images were acquired. For the analyses, the most favourable blocks of photos were adopted in terms of the recorded change in cloudiness, i.e. those blocks of photos with the smallest change in cloudiness. In addition, the moisture content of plants and soil in the botanic garden was controlled in a point-based manner, using moisture sensors. This allowed the values of the vegetation indices to be additionally related to the environmental factor of water deficiency.

3.5. Image post-processing and spectral indices

The acquired UAV image blocks, were processed in Agisoft Metashape software. Radiometric calibration was carried out for multispectral imagery to convert the raw Digital Number (DN) into a physical radiance value. Due to the variable illumination of the botanical garden at the time of aerial data acquisition, a calibration panel with known reflectance for the different ranges of recorded electromagnetic waves and parameters from the light sensor regarding ambient irradiance were used for the radiometric calibration. In order to carry out aerotriangulation of blocks of acquired images combined with simultaneous self-calibration of the UAV camera during its operation, natural terrain details were used as ground control points with known spatial coordinates. The results of the in-camera work were five-channel multispectral orthomosaics for two time periods and high-resolution RGB orthomosaics with a geometric resolution of 2 cm/pix. The mean squared error of the model fit on the 10 check points did not exceed $mp_{XYZ} < 20$ cm in any case. Multichannel multispectral orthomosaics were used to calculate the values of the characteristic spectral indices. High-resolution RGB orthomosaics, on the other hand, were used to support the interpretation of indicator values. In the present study, four spectral indices, computable from Micasense Red-Edge MX camera images, were determined as: NDVI, NDRE, GNDVI and PSRI.

The NDVI described by equation (1) is the most widely recognised and used spectral index for assessing plant development. Through its strong correlation with chlorophyll content, it allows the assessment of photosynthesis and monitoring activities during the plant growing season [28]:

$$NDVI = \frac{\rho_{NIR} - \rho_{RED}}{\rho_{NIR} + \rho_{RED}} \tag{1}$$

where ρ_{NIR} are DN values which are a measure of the reflectivity of electromagnetic radiation in the near-infrared (~0.84 μm), and ρ_{RED} values of the reflectivity of the red band of the optical radiation spectrum (~0.68 μm).

The NDRE spectral index has a similar application to the NDVI index cited earlier. The domain of both functions is also identical, being in the range <-1.0;1.0>. It is often used to assess the condition of plants for which the NDVI index quickly reaches high values [16]. It also allows the stress of the lower part of tall plants, rather than the top layer of crop crowns, to be assessed and is described by equation (2):

$$NDRE = \frac{\rho_{NIR} - \rho_{RED-EDGE}}{\rho_{NIR} + \rho_{RED-EDGE}} \tag{2}$$

where $\rho_{RED-EDGE}$ is the DN (Digital Number) values which is a measure of electromagnetic reflectivity at the red edge (~0.72 μm).

The GNDVI index is calculated based on equation (3). It has found general application in precision agriculture for monitoring plant water stress and photosynthesis [14, 17]. It is correlated with soil and plant nitrogen content and is therefore used to assess the quality of fertilisation of plant care areas and the uptake of nitrogen itself by crops:

$$GNDVI = \frac{\rho_{NIR} - \rho_{GREEN}}{\rho_{NIR} + \rho_{GREEN}} \quad (3)$$

where ρ_{GREEN} is the spectral channel with the recorded electromagnetic reflection in the green range (~0.56 µm).

The PSRI is sensitive to the ratio of carotenoids to chlorophyll. For Micasense Red-Edge MX camera images, calculated as in formula (4). An increased PSRI indicates increased stress in plants [28]:

$$PSRI = \frac{(\rho_{RED} - \rho_{BLUE})}{\rho_{RED-EDGE}} \quad (4)$$

where ρ_{BLUE} is the spectral channel with the recorded reflection of electromagnetic radiation in the blue range (~0.47 µm).

The raster algebra was carried out in the free software Qgis, in which the spatial maps of the previously mentioned spectral indices were also created. For all map compositions, the same region was chosen to enhance the significant features by using linear histogram stretching [29]. This made it possible to reliably compare the resulting maps of spectral indices between each other. The choice of spectral indices selected for the study was mainly dictated by the low spectral resolution of the Micasense Red-Edge MX camera. Initial data mining and statistical tests were performed in RStudio software, using the dplyr and sqldf libraries.

4. RESULTS

4.1. Maps of spectral indices

Processing of the acquired UAV images resulted in a high-resolution orthomosaic for each time period, followed by four maps of the spatial distribution of spectral indices. Due to the variable cloud cover during both measurement days, analyses on the reflectance maps were abandoned. By focusing only on the spectral indices, the influence of two factors on the results of the quantitative analyses, i.e., the variable illumination of the scene and the ground denivelations, was minimised. Figure 4 presents the resulting orthomosaics and maps of the calculated spectral indices from the first measurement series, conducted on 24.05.2022.

The correct progress of the vegetation process in the southern part of the botanical garden was confirmed on the maps of NDVI (Fig. 4b) and NDRE (Fig. 4c) indicators. This is evidenced by increased values of spectral indices (tones of blue color) relative to areas of poorer health (colors from orange to red). The lush vegetation in the southern complex is also confirmed by the high-resolution orthomosaic (Fig. 4a). The northeastern part of the botanical garden was being prepared for lily planting, hence the exposed soil and underestimated values of all spectral indices are evident. Increased PSRI values (Fig. 4e) indicative of additional plant stress, are mainly found among areas with exposed soil, which is justified by the increased temperature of these areas and thus increased vulnerability to drought. In contrast, the highest PSRI values (PSRI > 0.50) were recorded only for plants occurring in the azalea and heathland section. The thresholding of PSRI values was done by interpreting the PSRI map histogram and cutting off extreme outliers from the set. Subsequent batches of plants were analysed in detail. No anomalies were observed among the tall trees, confirming that the development of the trees is consistent with their phenology.

The values of the NDVI and NDRE indices in the central part of the botanical garden, in the complex of roses and azaleas (inside the marked red outline in Fig. 4a, right side) show underestimated values relative to nearby planted areas. The weakness of the plants in the garden section in question is also confirmed by the GNDVI index (Fig. 4d). This may indicate incorrect nitrogen uptake by the plants or washing away of applied fertilisers during rain, which is likely due to the high slope of the site. A similar trend was observed in the heathland section (inside the marked red outline in Fig. 4a, left side). Thus, both plant complexes were singled out as areas with a higher risk of plant stress and were subjected to detailed analyses in the remainder of the study. The results obtained confirm the problems already signalled by the Botanic Garden staff with the plant complexes mentioned. No disturbances were observed in the health condition of the plants located in the area of the 'East Asian Forest' section, which may mean that the preventive activities introduced have had a positive effect.

The localised anomalies shown in Figure 5a are characterised by a large contrast in the values of the spectral indices relative to other plants of the same type.

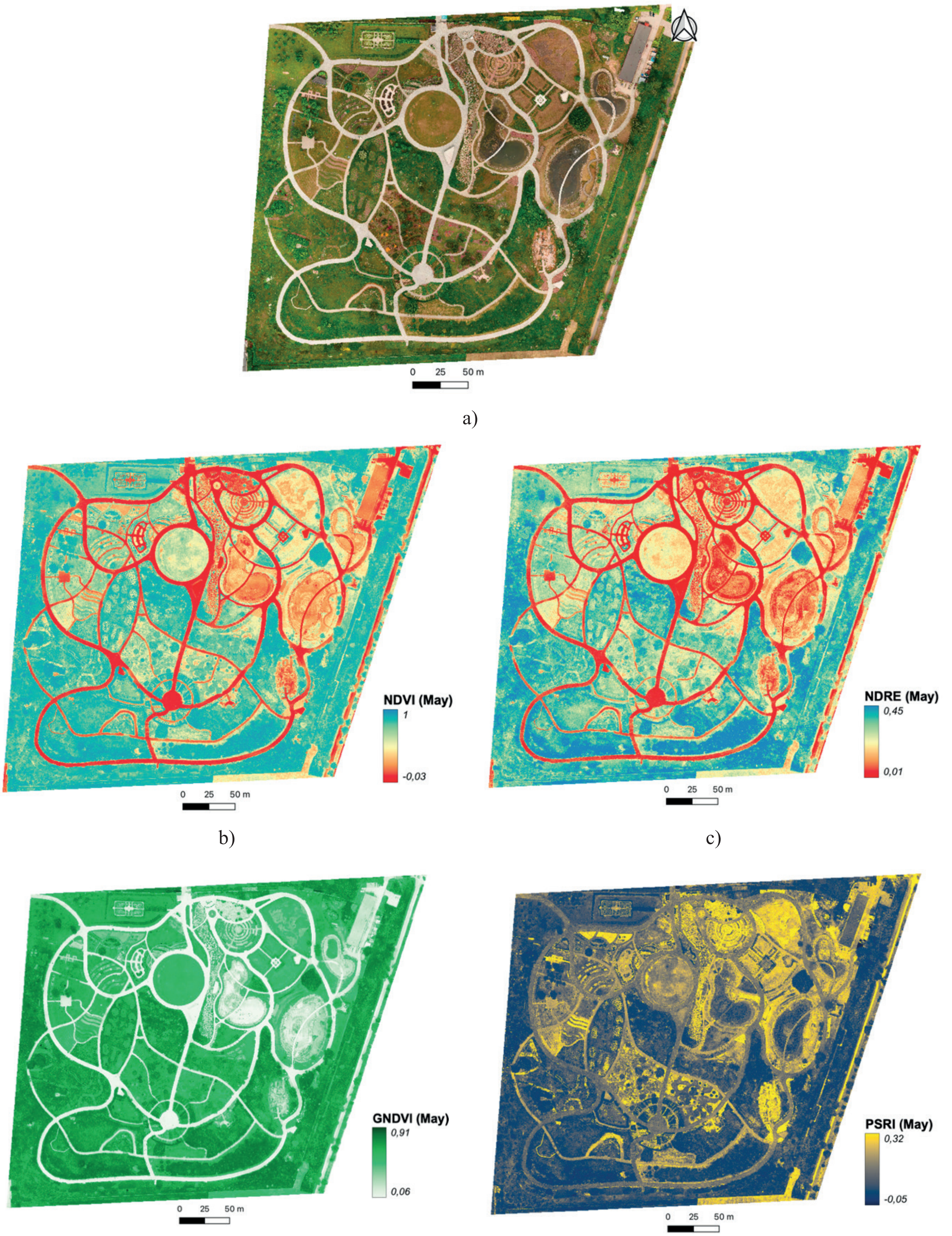


Fig. 4. Botanical Garden in Kielce for the first measurement series (may), presented as: a) orthomosaic, b) NDVI, c) NDRE, d) GNDVI, e) PSRI

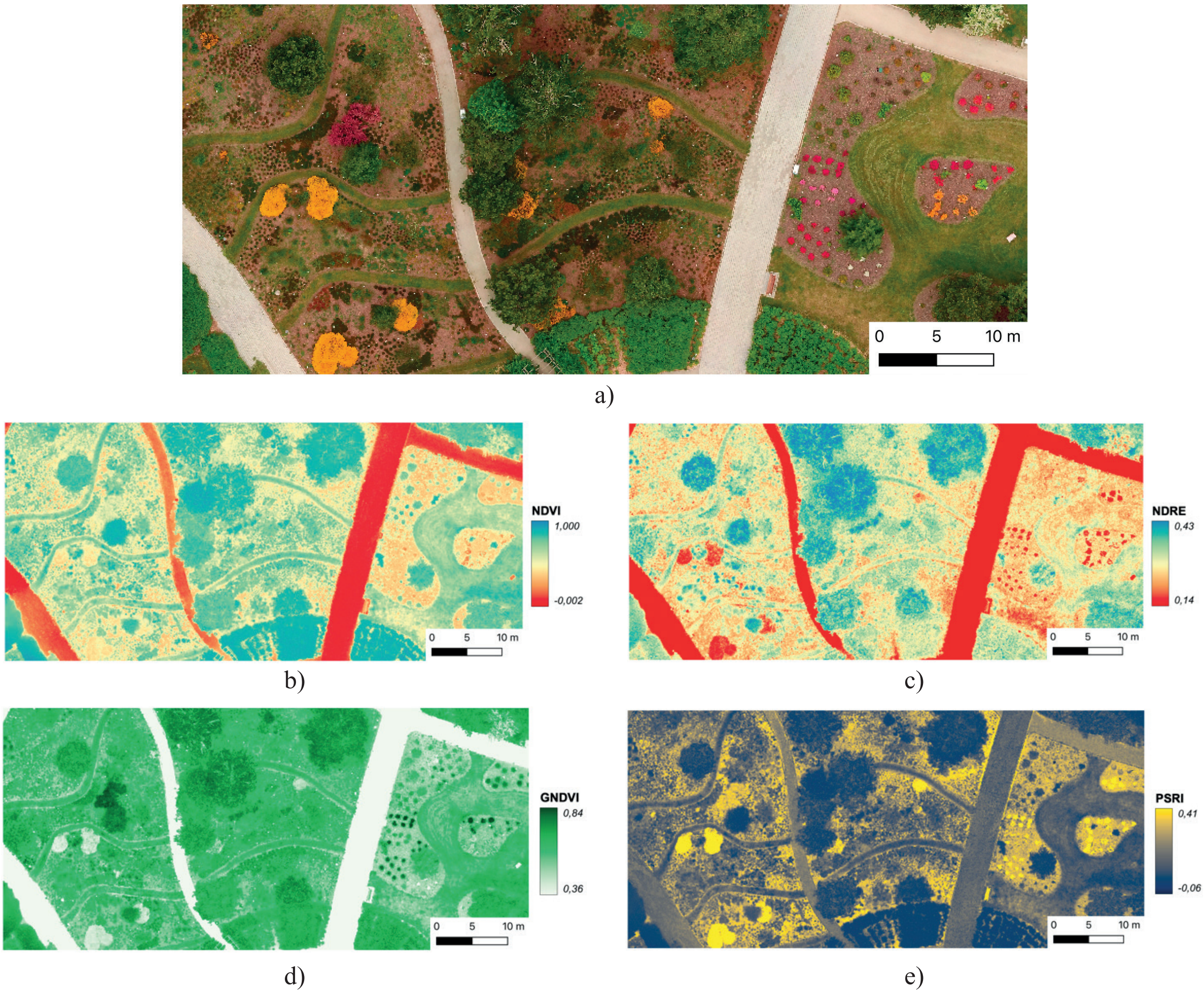


Fig. 5. Localized anomalies within the heathland (left side) and roses and azaleas (right side) sections of the botanical garden against: a) orthomosaic, b) NDVI, c) NDRE, d) GNDVI, e) PSRI

These anomalies may be due to the sensitivity of the two plant complexes presented earlier to changes in biochemical parameters in the form of chlorophyll and nitrogen concentrations. The chosen time period, i.e. the end of May, was advantageous for conducting environmental analyses due to favourable and stable atmospheric conditions preceding the UAV flight carried out – low rains, temperatures oscillating in the range of 16-20°C. On the basis of in situ measurements, the factors of waterlogging and drought were additionally excluded as factors that could negatively affect the development of plants during their growing season. The NDVI (Fig. 5b) and NDRE (Fig. 5c) indices confirm that plant development abnormalities affect not only the upper plant layer, but also the flowers located under the upper crown. Neither the NDRE and GNDVI index (Fig. 5d) can clearly determine whether the reason for the disturbance is a problem with the absorption of organic compounds by the plants or a reduced alpha/beta chlorophyll content. Noteworthy is the PSRI index (Fig. 5e), which, after threshold reclassification, is the only one that directly typifies the plants presented for detailed analysis. This means that the PSRI can help improve monitoring activities to ensure the correct health of the plants in the Kielce Botanic Garden.

4.2. Temporal variation of spectral indices

The analysis of the variability of the values of the spectral indices was intended to find additional anomalies occurring inside the study object and to assess the prevention activities carried out in terms of localised disturbances in Figure 5. The second measurement series was carried out on 13.07.2022 (the results are included in Appendix 1). Figure 6 shows maps of the differences in the spectral indices NDVI, NDRE, GNDVI and PSRI between the two time periods analysed in the study.

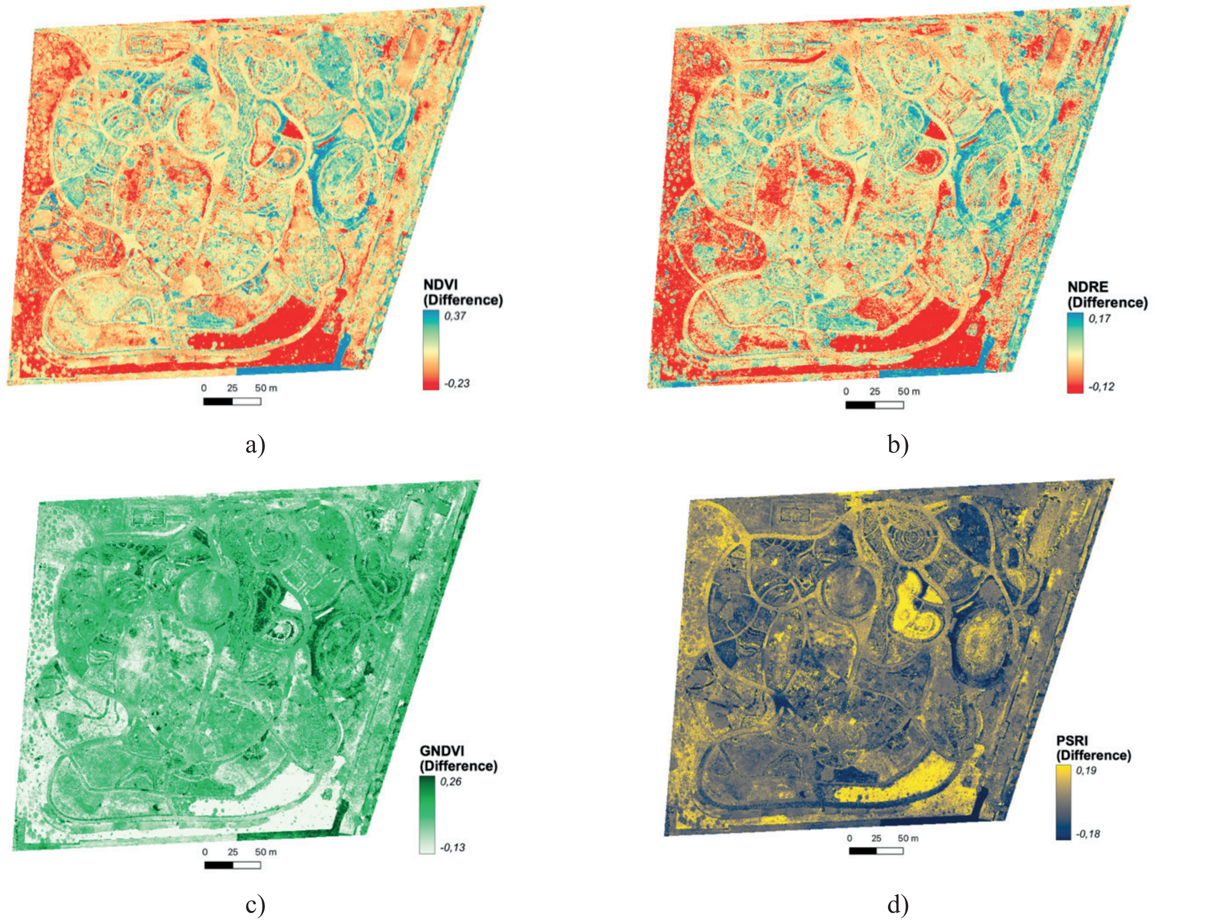


Fig. 6. Maps of differences in the values of spectral indices for the period May-July 2022: a) NDVI, b) NDRE, c) GNDVI, d) PSRI

The values of NDVI (Fig. 6a) and NDRE (Fig. 6b) differ significantly in the analysed period May-July. One of the reasons for this phenomenon, may be the weather conditions. The second UAV flight with the multispectral camera, was made after a prolonged period of sustained high temperatures and low rainfall. The drought factor was confirmed by in situ surveys. The soil moisture of the upper parts of the plants (north-facing) was only slightly lower than the soil moisture within the plant complex on the southern slope.

It should be noted that many of the plant genotypes present in the garden have different growing seasons. This in turn affected the values of the indices obtained from the different data acquisition periods. The values of NDVI and NDRE differences are also influenced by the soil background, which retouches the purity of the untreated spectral samples and affects the result of the quantitative analyses. This phenomenon is of particular importance in the context of the interpretation of all the indices presented in this paper for the north-eastern area of the garden, originally dominated by a large part of the exposed soil. The decrease in the value of the GNDVI index (Fig. 6c) in the south-eastern part of the garden indicates a weaker vegetation pattern of the plants constituting the East Asian Forest section. This may indicate that the plants are past their peak growing season. The ratio of existing trees and shrubs in the East Asian woodland section to low vegetation (grasses) is low. The pruning of grasses prior to the period of increased heat may have led to increased vulnerability to grass infestation due to high temperatures and additional soil exposure – for which NDVI, NDRE and GNDVI values are generally lower. No grass withering was observed on the eastern side of the botanical garden, which is probably due to the large number of tall trees on this side of the garden, which provided shade for the surrounding plants. The PSRI difference map (Fig. 6d) did not identify areas of increased stress on the grown plants in this case with the exception of the previously mentioned grasses.

A preliminary comparison of the processed control images from the Micasense Red-Edge MX multispectral camera for both time periods analysed, confirmed the observations made earlier. The areas presented in Figure 5 showed vegetation progression during the July period by increasing NDVI, NDRE and GNDVI values while decreasing PSRI. This means that the early diagnosis of the botanic garden's listed sections of roses and azaleas and the heathland as areas of abnormal plant growth enabled preventive treatments to be implemented effectively and correctly.

5. STATISTICAL ANALYSES

In order to perform a detailed analysis for the entire study site (Fig. 4) and areas with identified abnormalities with increased stress (Fig. 5), statistical parameters were calculated for the spectral indices used. Figure 7 shows their distribution along with their standard deviations for plants from the entire botanical garden. Only plant sections inside the botanic garden were considered for the calculation of the signatures. Areas of anthropogenic activity, artificial field details and shaded areas were excluded from the analysis. Nevertheless, during the initial data mining, outlier observations were noted from the entire data set. In order to eliminate their influence, the mean values of the spectral indices were calculated using a truncated average, trimming the minimum and maximum values with a threshold of 5%. The large values of individual standard deviations are due to the biodiversity of the cultivated plant specimens in the botanic garden.

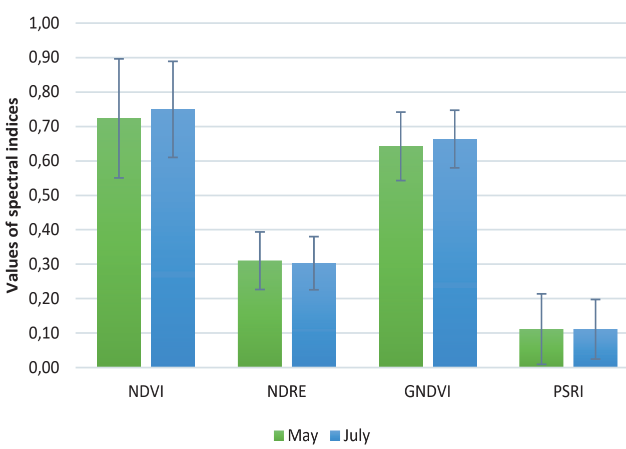


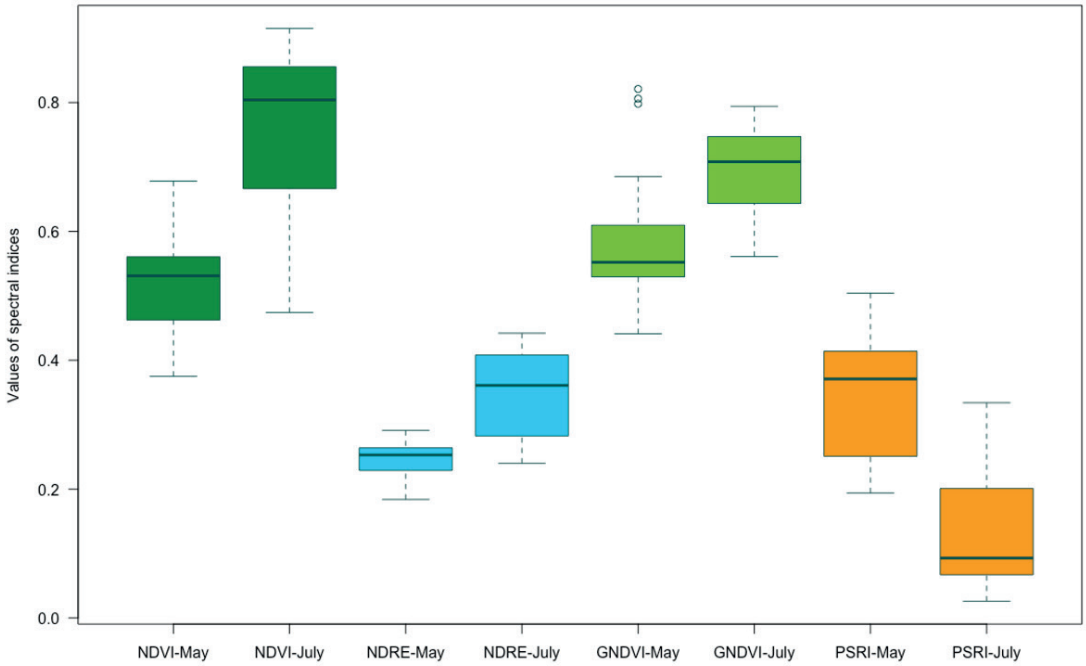
Fig. 7. Graph of the distribution of mean values of the analysed spectral indices for the period May-July, for the biologically active area of the botanic garden

The average NDVI values presented in Figure 7 increased in July, which in the present case means that the organic matter content increased. This is also confirmed by the observed upward trend in the GNDVI index. During the first measuring series, there was a large amount of exposed soil prepared for the planting of further plant varieties. During the second measurement series, the area of exposed soil decreased due to the vegetation of later crop maturing. The mean value of the NDRE index decreased on 13 July compared to 24 May. This may indicate a better response of the NDRE index to plant water stress than the NDVI index. The reduction in plant and soil moisture during May-July was confirmed by in situ studies. The average values of the PSRI for the botanical garden plants in both analysed time periods, remained at a similarly low level. This result attests to the correct application of agrotechnical procedures and the high quality of plant care in the area of the entire botanic garden in Kielce.

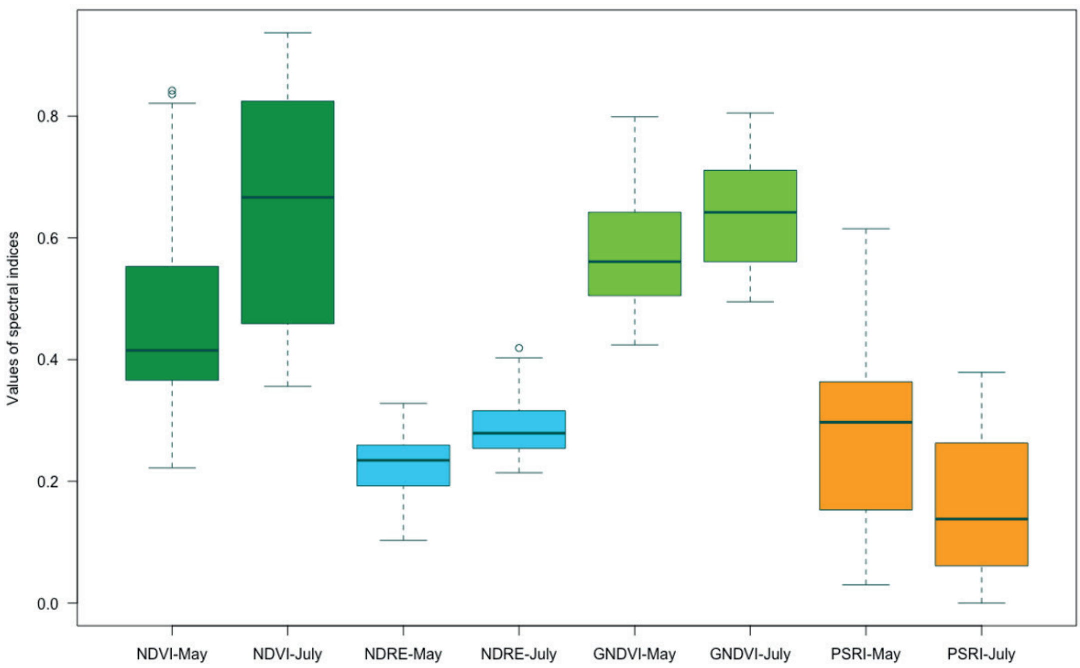
The distribution of the scatter plots of spectral indices for the problematic plant complexes, which included heathland, azalea and roses (Fig. 5a), is presented in Figure 8. No extreme outlier observations were observed in any of the analysed cases. Figure 8a shows the quantiles of the distribution of spectral indices for the heathland. The largest scatter in the data occurred for the NDVI in July, for which half of the observations are in the range 0.45-0.80. The values of the PSRI in the heathland are significantly higher in May compared to the values of the PSRI in July – for which the observations in the second quantile are in the range 0.05-0.10. A similar trend in the values of the spectral indices for the analysed time periods occurs for the second problematic plant division (Fig. 8b). The conclusions obtained from the box plot analysis confirm the effectiveness of the applied preventive measures within the heathland, azalea and roses complex.

Due to the large ranges of the indicated index groups in Figure 8, it was decided to check the statistical significance of the obtained differences in spectral indexes for the analysed May-July time period. For this purpose, the student's t-test was used, assuming a normal distribution of the index values. The null hypothesis referred to the absence of significantly statistical differences between the NDVI, NDRE, GNDVI and PSRI index groups. The test results for the two problematic sections of the botanical garden are presented in Table 2.

The results of the student's t-test performed confirm the validity of the alternative hypothesis in each variant. The alternative hypothesis was that the obtained differences in the NDVI, NDRE, GNDVI and PSRI spectral index values are statistically significant.



a)



b)

Fig. 8. Scatter plots of spectral indices for (a) heathland section, (b) azalea and roses section

Table 2. Summary of p-value results from Student's t-test (α = 0.05)

Name of the plant section	**Heathlands**				**Azaleas and roses**			
Comparable spectral indices for the period May - July	NDVI	NDRE	GNDVI	PSRI	NDVI	NDRE	GNDVI	PSRI
***p*-value**	< 0.001	< 0.001	0.002	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001

6. SUMMARY AND CONCLUSIONS

This paper confirms that measurement methods involving low-altitude remote sensing techniques are useful for the correct detection of plant stress with unique flora and complex spatial characteristics. Remote sensing using unmanned aerial vehicles not only has the advantages of flexibility in terms of prevailing atmospheric conditions, high speed and high resolution of the acquired images, but also real-time advantages. Thus, the processing results of multispectral images from UAVs make it possible to effectively compensate for some of the disadvantages of ground-based measurements.

Failure to detect early stress in plants can result in stress extending beyond the recovery period of the nurtured flowers, causing vegetation dieback on a much larger scale. On the site of the botanical garden in Kielce, the vegetation problem of the heathland, azalea and roses complex was identified by mapping the NDVI, NDRE, GNDVI and PSRI spectral indices (Fig. 5). The PSRI index values, after thresholding PSRI > 0.50, clearly identified areas of high stress. This confirms the applicability of the PSRI index to conduct monitoring activities in botanical garden areas in an efficient and rapid method. The results obtained are identical to the predictions of the specialists working in the botanic garden presented.

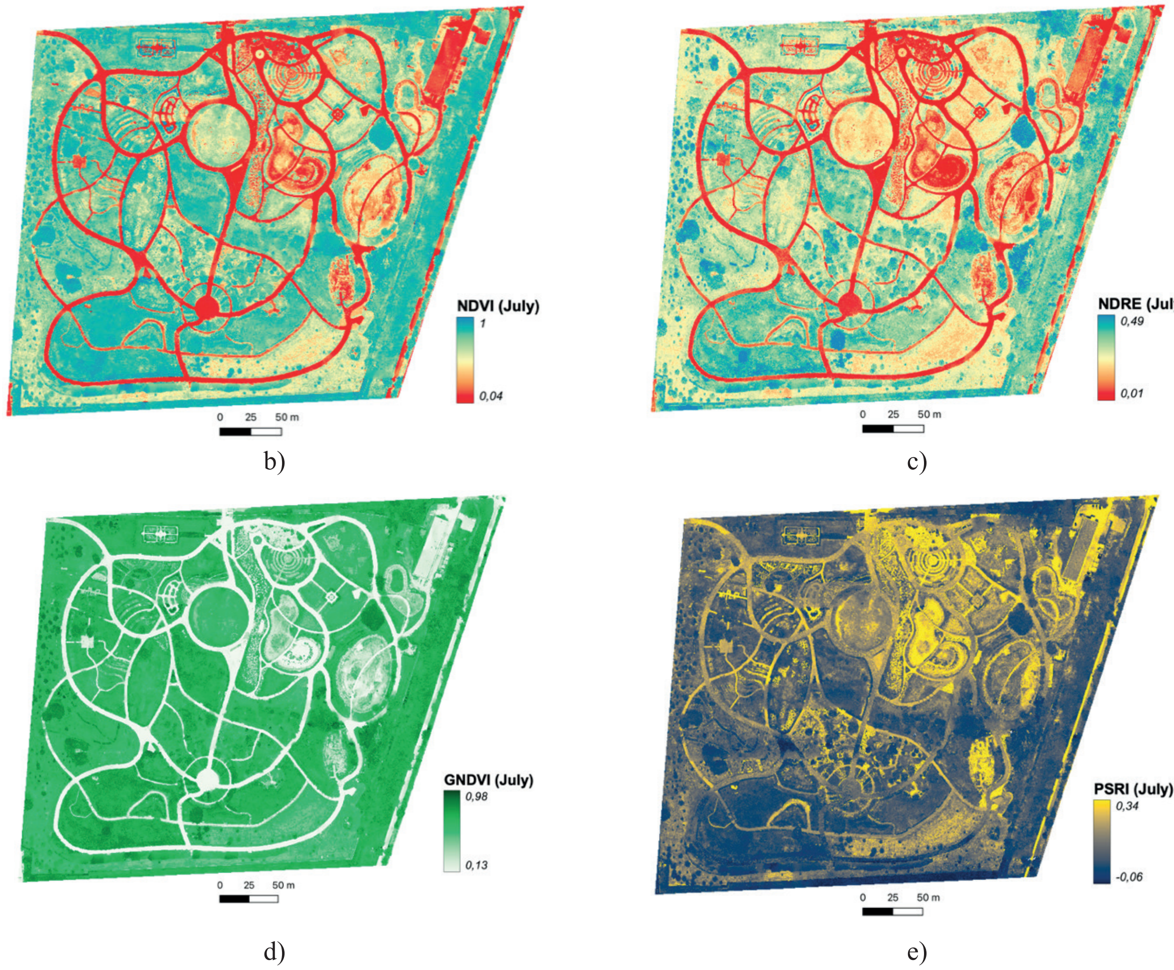
Performing analyses on the processed remote-sensing images, for different vegetation periods, made it possible to identify the state of the greenery under study and to verify predictions of the vegetation course. The differences in the values of the spectral indices obtained for the May-July time period were found to be statistically significant (Table 2). Thus, the correct health condition of plants in the month of July and the effectiveness of preventive measures carried out in the botanic garden area were confirmed.

High-resolution satellite imagery remains expensive for many ecological applications – mainly due to the need to purchase the entire satellite scene, rather than the slice of area needed for analysis. In contrast, the cost of acquiring UAV imagery is rapidly decreasing, making it a potential tool for monitoring individual plants and local landscapes. Precision agriculture regularly uses high-resolution drone imagery, and the declining cost of low-altitude imagery is also making the technology accessible to ecologists.

UAV remote sensing is a critical tool to fill the time gap in satellite data for crop and plant monitoring. This paper demonstrates the usefulness of the Micasense Red-Edge MX camera to locate areas of high stress in advance, while enabling proactive management of plant complexes to improve the performance of the entire botanical garden.

APPENDIX

a)



Botanical Garden in Kielce for the second measurement series (July), presented as: a) orthomosaic, b) NDVI index, c) NDRE index, d) GNDVI index, e) PSRI index

References

[1] Neupane K., Baysal-Gurel F.: *Automatic identification and monitoring of plant diseases using unmanned aerial vehicles: A review*, Remote Sens (Basel), vol. 13, no. 19, 2021, doi: 10.3390/rs13193841.

[2] Stupen R., Ryzhok Z., Stupen N., Stupen O.: *The modeling of the yielding capacity of winter cereals due to satellite monitoring data of agricultural lands in Ukraine*, Geodesy and Cartography, vol. 47, no. 1, pp. 1-9, 2021, doi: 10.3846/gac.2021.11740.

[3] Radoglou-Grammatikis P., Sarigiannidis P., Lagkas T., Moscholios I.: *A compilation of UAV applications for precision agriculture*, Computer Networks, vol. 172, 2020, doi: 10.1016/j.comnet.2020.107148.

[4] Marzec P.: *Wykorzystanie wskaźników spektralnych do monitoringu stresu roślin na terenie ogrodu botanicznego w Kielcach*, Master Thesis, Kielce University of Technology, 2022.

[5] Vanegas F., Bratanov D., Powell K., Weiss J., Gonzalez F.: *A novel methodology for improving plant pest surveillance in vineyards and crops using UAV-based hyperspectral and spatial data*, Sensors (Switzerland), vol. 18, no. 1, pp. 1-21, 2018, doi: 10.3390/s18010260.

[6] Hunt E.R., Dean Hively W., Fujikawa S.J., Linden D.S., Daughtry C.S.T., McCarty G.W.: *Acquisition of NIR-green-blue digital photographs from unmanned aircraft for crop monitoring*, Remote Sens (Basel), vol. 2, no. 1, pp. 290-305, 2010, doi: 10.3390/rs2010290.

[7] Mularz S., Drzewiecki W., Pirowski T.: *Teledetekcyjne metody rejestracji krajobrazu*, Roczniki Geomatyki, vol. V, no. 8, pp. 67-80, 2007.

[8] Warchoł A.: *Analiza dokładności przestrzennej danych z lotniczego, naziemnego i mobilnego skaningu laserowego jako wstęp do ich integracji*, Archiwum Fotogrametrii, Kartografii i Teledetekcji, vol. 25, pp. 255-260, 2013.

[9] Smith P.: *The challenge for botanic garden science*, Plants People Planet, vol. 1, no. 1, pp. 38-43, 2019, doi: 10.1002/ppp3.10.

[10] Drzewiecki W.: Land-Use / Land Cover Monitoring Based on Multitemporal Remote Sensing Images, Roczniki Geomatyki, vol. VI, no. 3, pp. 132-142, 2008.
[11] Velusamy P., Rajendran S., Mahendran R.K., Naseer S., Shafiq M., Choi J.-G.: Unmanned Aerial Vehicles (UAV) in Precision Agriculture: Applications and Challenges, Energies (Basel), vol. 15, no. 217, pp. 1-19, 2022, doi: https://doi.org/10.3390/en15010217.
[12] Balawejder M., Matkowska K., Colak H.E.: The Impact of Surveying Works on the Development of Smart City, Geographic Information Systems Conference and Exhibition "GIS ODYSSEY 2018", no. 2623-5714, pp. 20-32, 2018.
[13] Hejmanowska B., Twardowski M., Żądło A.: An application of the "traffic lights" idea to crop control in integrated administration control system, Geomatics and Environmental Engineering, vol. 15, no. 4, pp. 129-152, 2021, doi: 10.7494/geom.2021.15.4.129.
[14] Sagan V. et al.: UAV/Satellite multiscale data fusion for crop monitoring and early stress detection, International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, vol. 42, no. 2/W13, pp. 715-722, 2019, doi: 10.5194/isprs-archives-XLII-2-W13-715-2019.
[15] Curnel Y., Oger R.: Agrophenology Indicators From Remote Sensing: State of the Art, Isprs.Org, pp. 31-38, 2007, [Online]. Available: http://www.isprs.org/proceedings/XXXVI/8-W48/31_XXXVI-8-W48.pdf.
[16] Luo D. et al.: Using UAV image data to monitor the effects of different nitrogen application rates on tea quality, J Sci Food Agric, vol. 102, no. 4, pp. 1540-1549, 2022, doi: 10.1002/jsfa.11489.
[17] Scher C.L. et al.: Application of remote sensing technology to estimate productivity and assess phylogenetic heritability, Appl Plant Sci, vol. 8, no. 11, pp. 1-14, 2020, doi: 10.1002/aps3.11401.
[18] Rafa N., Nuzhat S., Uddin S.M.N., Gupta M., Rakshit R.: Ecotourism as a forest conservation tool: An ndvi analysis of the sitakunda botanical garden and ecopark in chattogram, bangladesh, Sustainability, vol. 13, no. 21, 2021, doi: 10.3390/su132112190.
[19] Minh Chinh L.: Using Satellite Images To Retrieve the River Turbidity and Water Flow Velocity for Monitoring Their Influences on Bridge Substructures, Structure and Environment, vol. 15, no. 2, pp. 63-72, 2023, doi: 10.30540/sae-2023-006.
[20] Backoulou F.G., Elliott N., Giles K., Alves T., Brewer M., Starek M.: Using multispectral imagery to map spatially variable sugarcane aphid infestations in sorghum, Southwest. Entomol, vol. 43, pp. 37-44, 2018, doi: https://doi.org/10.3958/059.043.0122.
[21] Feng L., Chen S., Zhang C., Zhang Y., He Y.: A comprehensive review on recent applications of unmanned aerial vehicle remote sensing with various sensors for high-throughput plant phenotyping, Comput Electron Agric, vol. 182, 2021, doi: 10.1016/j.compag.2021.106033.
[22] Liang H., Li W., Lai S., Zhu L., Jiang W., Zhang Q.: The integration of terrestrial laser scanning and terrestrial and unmanned aerial vehicle digital photogrammetry for the documentation of Chinese classical gardens – A case study of Huanxiu Shanzhuang, Suzhou, China, J Cult Herit, vol. 33, pp. 222-230, 2018, doi: 10.1016/j.culher.2018.03.004.
[23] Hajdukiewicz M., Romanyshyn I.: An accuracy assessment of spot heights on Digital Elevation Model (DEM) derived from ALS survey: case study of Łysica massif, Structure and Environment, vol. 9, no. 2, pp. 125-132, 2016.
[24] Zhang Y., Song C., Sun G., Band L.E., Noormets A., Zhang Q.: Understanding moisture stress on light use efficiency across terrestrial ecosystems based on global flux and remote-sensing data, J Geophys Res Biogeosci, vol. 120, no. 10, pp. 2053-2066, 2015, doi: 10.1002/2015JG003023.
[25] Geonatura Kielce – Botanical Garden website. Accessed: Nov. 20, 2022. [Online]. Available: https://geonatura-kielce.pl/ogrodbotaniczny/informacje-ogolne/.
[26] Sobura S.: Calibration of the Low-Cost Uav Camera on a Spatial Test Field, Geodesy and Cartography, vol. 48, no. 3, pp. 134-143, 2022, doi: 10.3846/gac.2022.16215.
[27] Micasense producer website. Accessed: Nov. 20, 2022. [Online]. Available: https://support.micasense.com/hc/en-us.
[28] Sobura S., Hejmanowska B., Widłak M., Muszyńska J.: *The Application of Remote Sensing Techniques and Spectral Analyzes to Assess the Content of Heavy Metals in Soil – A Case Study of Barania Góra Reserve*, Poland, Geomatics and Environmental Engineering, vol. 16, no. 4, pp. 187-213, 2022, doi: 10.7494/geom.2022.16.4.187.
[29] Pyka K.: *Wavelet-based local contrast enhancement for satellite, aerial and close range images*, Remote Sens (Basel), vol. 9, no. 1, 2017, doi: 10.3390/rs9010025.

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