SYLWAN 167 (10): 650-665, October 2023
https://doi.org/10.26202/sylwan.2023027
Journal homepage: https://sylwan-journal.pl

ORIGINAL PAPER

Dynamics of autumn discoloration of tree crowns in sessile oak stand based on the time series of low-altitude aerial photographs

Krzysztof Będkowski(1,3)✉, Paweł Szymański(2,3,4)

(1) University of Lodz, Faculty of Geographical Sciences, S. Kopcińskiego 31, 90-142 Łódź, Poland

(2) State Forests – Jabłonna Forest District, Wiejska 20, 05-110 Jabłonna, Poland

(3) Polish Geographical Society – Remote Sensing Branch, Krakowskie Przedmieście 30,
00-927 Warszawa, Poland

(4) Polish Forestry Society, Bitwy Warszawskiej 1920 r. nr 3, 02-362 Warszawa, Poland

ABSTRACT

Based on a series of multitemporal aerial photographs taken with a drone, we investigated the course of phenological phenomena in autumn in a stand of sessile oak *Quercus petraea* in central Poland. We assumed that the colours of tree crowns visible in RGB photos are a visible symptom of their state of preparation for winter rest. The classification of trees was made based on a visual assessment of colours. Oaks were divided into 7 classes – from green to brown with a large loss of assimilation apparatus. The trees that were the fastest to rest were those in which the earliest symptoms of changes in leaf colour were observed. However, about $^1/_{10}$ of trees maintained green or slightly altered foliage throughout most of the investigation period.

The most important conclusion resulting from the conducted research is the statement of the fact that the colours of crowns that can be observed at a given moment in the stand are not always a good indicator of the order in which trees go to winter dormancy. Some trees went to winter dormancy faster than others, and faster than could be expected from previous observations.

KEY WORDS

autumn phenology, senescence, sessile oak, UAV images

Introduction

Global climate change affects the course of periodic phenological phenomena in trees and shrubs, such as spring development of leaves, flowering, fruiting and discoloration, and leaf fall at the end of the growing season. In many species, an extension of the growing season is observed, which results from the earlier start of spring rushing and the delay in the transition to winter dormancy, with the postponement of the dates of phenological phenomena being more clearly visible in the spring period (Vitasse *et al.*, 2011). Differences in phenological development of trees and shrubs are observed between species, their populations and individual specimens. Individual species develop the assimilation apparatus in spring in a fixed order, repeated in subsequent seasons (Lechowicz, 1984; Wesołowski and Rowiński, 2006). Similar differences in development are

✉e-mail: krzysztof.bedkowski@geo.uni.lodz.pl

Received: 4 May 2023; Revised: 27 November 2023; Accepted: 18 December 2023; Available online: 12 January 2024

observed in the fall, when the trees are preparing for winter dormancy. Some species are considered to be determinants of the length of the growing season, *e.g.* the development of leaves of common hazel *Corylus avellana* L. marks its beginning, while discoloration and leaf fall in birch *Betula pendula* Roth is a sign of its end (Zaręba, 1952). In numerous provenance experiments of various tree species, it has been shown that the dates of leaf development, changes in their colour in autumn, dying and falling, as well as the persistence of dead leaves on trees in winter are related to the longitude, latitude and altitude above sea level of the place of origin of a given population. Trees of southern provenance started the growing season faster, while those of northern provenance – later (Schlarbaum and Bagley, 1981; Ducousso *et al.*, 1996; Kadomatsu, 1997; Fenner, 1998; Davi *et al.*, 2011). Differences in the course of phenological phases are also observed between individuals growing in the same stand. The reasons for the uneven pace of development are seen in the spatial diversity of habitat quality, minor differences in microclimate, variability of vertical and horizontal stand structure affecting the density of trees, the position occupied on the outskirts or inside the stand (Trąba *et al.*, 2012), or in differences in access to light (Weidler and Sivanpillai, 2020).

Changes in the dates of phenological phases, especially the development of the assimilation apparatus, as well as flowering and fruiting, can significantly affect insect populations that need an appropriate food base for their development (Kiełczewski, 1962). The leaves of trees infested by insects that mine and form galls discolour and fall earlier (Waddel *et al.* 2001, Kot *et al.*, 2018), but the opposite effect is also known – delays in leaf fall (Ekholm *et al.*, 2019). Also, the fact that trees are overrun by fungi may affect the course of phenological phenomena throughout the growing season (Włoczewski, 1953). As Soto *et al.* (2017) point out, the course of autumn phenological changes may be a specific indicator of habitat quality associated with the distribution of, for example, woodpeckers. The timing of the various phenological symptoms is not always fixed for a given tree specimen, and may vary from year to year, so that trees with some phenological symptoms relatively early in one year may exhibit them later than other individuals in another (Bacilieri *et al.*, 1995). The literature also points to different effects of extending the growing season, especially accelerating its beginning, on the growth of trees. According to Vitasse *et al.* (2011), the acceleration of development in spring and the subsequent completion of vegetation in autumn may affect the phenomena of interspecific competition and, as a result, changes in the spatial range of species. It was also noted that the extension of the growing season is affected more strongly by early development in spring than by its extension in autumn (Chmielewski and Rötzer, 2001; Vitasse *et al.*, 2011; Kolář, 2016).

In Poland, two species of oaks – pedunculate *Quercus robur* L. and sessile *Q. petraea* (Matt.) Liebl. are important forest-forming species (Andrzejczyk, 2009). These species differ in terms of biological features and habitat requirements – the pedunculate oak prefers more fertile and moist habitats, compared to the habitats preferred by the sessile oak (Zaręba, 1962, 1993; Markowski, 1993), but they also often occur in the same stands (Boratyński, 1994; Ducousso, *et al.*, 1996; Boratyński *et al.*, 1997; Boratyński and Sztajnborn, 2001) and form hybrids, whose share in the stand is generally small. Similar course and variability of phenological phenomena were observed in both species (Bacilieri *et al.*, 1995). For example, they exhibit characteristic, significant differences in the development of individual specimens, even those growing in a stand close to each other (Adamowski, 2008). It is therefore believed that there are two forms of oaks – early and late, and the differences in development between them can sometimes reach up to several weeks and recur in subsequent years (Crawley and Akhteruzzaman, 1988).

Both early development and delaying the transition to winter dormancy prolong the growing season, but different authors note their different effects on tree growth. It is indicated that longer activity of a given individual during the growing season allows it to gain an advantage over other trees. Samek (1988) and Polgar and Primack (2011) observed greater stem volume gain in pedunculate oak trees with a longer growing season. Hernik (1973), on the other hand, writes that early developing pedunculate oaks are lower than late form oaks. He also observed differences in the average stem volume of a single tree – oaks that developed leaves later had a higher volume than trees that had developed them earlier. However, these differences were considered minor and of no practical importance. Samek (1988) noticed that oaks that have long kept green leaves are characterised by longer cambium activity during the growing season than others. This results in larger annual increments and, as a result, larger diameters at breast height (DBH).

In provenance studies, high population variability of oak was found. Polish oak provenances are described as significantly diverse in terms of fitness and growth, as well as phenological features (Fijałkowski, 1968a; Barzdajn, 2000). At the same time, it is indicated that the variability of oaks has not been sufficiently studied, as there have only been a few provenance experiments (Barzdajn, 2004). The research described by Fober and Rożkowski (2006) confirms earlier reports from the literature about the high variability of many qualitative and quantitative traits. Kleinschmit (1993) states that phenological features in both oak species show both clinal and ecotypic variability. In phenological studies, phenomena occurring in autumn are much less frequently studied compared to those occurring in spring. Leaf senescence is associated with the withdrawal of nutrients from the leaves into the body of the plant and seeds. This process consists of a series of coordinated phenomena occurring at the level of cell, tissue, organ and the whole organism under the control of a highly regulated genetic programme (Lim *et al.*, 2006). The visual effect is the discolouration of leaves from green to yellow, sometimes red, and then to brown, followed by leaf fall. Colour changes result from faster degradation of chlorophyll compared to carotenoids and the developing synthesis of red-coloured pigments (Keskitalo *et al.*, 2005 after Godwin 1958 and Lichtenthaler, 1987). Changes in the spectral characteristics of plants at this time consist in a significant decrease in the reflection of green and infrared radiation and an increase in the reflection of red radiation (Olędzki, 1993). The occurrence of the first symptoms of autumn aging of leaves is associated with shortening daytime and decreasing temperature. Under the influence of water deficit, the leaves discolour, and the so-called cut-off zones are formed at the base of the petioles. The reactions occurring there cause a weakening of cohesion between cells, and finally – leaf fall (Kozłowska, 2007), although they may also remain (up to about 40%) until spring (Fijałkowski, 1968b). According to Škvareninová *et al.* (2008), the most important factors determining the date of termination of photosynthetic activity by trees, expressed in the onset of leaf discolouration, are air temperature, light availability and moisture conditions in summer, with leaf discolouration occurring earlier in dry seasons. High temperatures in August and September delay autumn colour changes, but moisture deficiency in September, May and June leads to accelerated discoloration of oak leaves (Estrella and Menzel, 2006). It may be thought that these observations relating to certain populations can also be considered as causes of differences between individuals. It is known that trees with smaller diameters at breast height and trees characterised by narrower growth in thickness begin the process of autumn discolouration of leaves and fall earlier, regardless of the age of the stand (Samek, 1988). Hernik (1973) noticed that early oaks underwent the autumn discolouration of leaves an average of four days earlier than the late form. He also noted that the growing season was longer in early-growing oak.

Changes in the phenological state of plants are very well visible from the aerial perspective. Remote sensing makes it possible to identify plants and their condition, using such features as: colour, internal and external structure of leaves, as well as leaf shape and crown structure (Boyer *et al*., 1988; Merzlyak *et al*., 1999; Sims and Gamon, 2002; Lisein *et al*., 2015). In studies on changes in plant albedo during the year, it has been shown that the coefficients for visible light change with the progressive aging process of leaves, in contrast to infrared radiation (Olędzki, 1993). It has also been shown (Łoziński and Będkowski, 2016) that using RGB images taken with UAVs, it is possible to carry out a high-accuracy visual classification of autumn phenological phases of oaks, as well as to trace the dynamics of their changes (Będkowski and Stereńczak, 2013).

Observation and analysis of phenological phenomena in spring and autumn will allow for a better understanding of the importance of the length of the growing season for the development of individual trees in the stand, and in particular for the development of their characteristics (DBH, height, stem volume) and sensitivity to climatic factors (late and early frosts), as well as their impact on the trees condition. It will also allow for selecting trees for permanent observation in order to determine whether these phenomena take place each year in a similar chronological order, whether they are heritable and what relationships they have with the presence of foliophages or fungi, as well as the course of meteorological phenomena.

The aim of the research presented in this paper is to analyse the dynamics of autumn changes in the colours of the assimilation apparatus of individual trees and the stand of sessile oak, using UAV imagery.

Materials and methods

STUDY AREA. The research concerns approx. 90-year-old, at the time of observation, stand of sessile oak *Quercus petraea*, with an area of 7.49 ha, located in the area administered by the Forest Experimental Station in Rogów – a field research centre of the Warsaw University of Life Sciences (19.920365°E, 51.837381°N). In the upper storey of the stand, there is almost exclusively sessile oak – according to the inventory description, the share of Scots pine *Pinus sylvestris* L. does not exceed 10%. The crown closure is full, moderate in places. In the understorey there are fir *Abies alba* Mill. and hornbeam *Carpinus betulus* L., while the undergrowth is dominated by hazel *Corylus avellana* L. According to the measurements made in spring 2016, oaks reached about 30 m in height, and their DBHs were 19.3÷56.0 cm, with an average of 35.2 cm. The terrain is flat, with a slight slope towards the north-west. The course of spring phenological phenomena in 2016 in the same stand was studied by Będkowski (2018) based on repeated ground observations.

DATA ACQUISITION. In the autumn of 2016, low-altitude images of the stand were taken in natural colours (RGB) using on-board camera carried by the DJI Phantom 4 unmanned aerial vehicle. The camera is able to record at a resolution of 12 MP (4000×3000 pixels, on a 1/2.3" sensor with ISO range of 100-3200). Weekly image acquisition was planned, from the end of September to the beginning of November, but due to unfavourable weather conditions, it was possible to obtain acceptable material from only four dates: 8, 22, 30 October and 6 November 2016. We knew, however, that defoliation is so advanced at the beginning of November that it hinders the work of automatic algorithms whose task is to create orthomosaics from the obtained photos. These algorithms use the technique of correlating images and they ‘get lost’ in the absence of clear objects in the images, which is the case with increasing defoliation. This rather random choice, however, finds some basis in the study of Chojnacka-Ożga and Ożga (2023), in which we read that in the Experimental Forests in Rogów, the end of the forest growing season, *i.e.* with an average daily temperature falling below 10°C, falls on average on October 5, while the date of the end of the thermal growing season (average daily temperature falling below 5°C) is gradually shifting (delaying) and in recent years it has fallen on average on November 1. The characteristics of flights and orthomosaics obtained are shown in Table 1. Due to deteriorating conditions (progressive defoliation), we increased the range of the flights to obtain images of more details, which later helped with the automatic production of orthomosaics.

Data processing. The photos were transmitted to computing cloud servers from Drone Deploy, which allowed for obtaining a finished image, *i.e.* the orthomosaic and Digital Surface Model. Images were processed using the 'structure' mode. This is a function that allows for the creation of more precise orthophotomosaics and a digital model of land cover in the event of significant height differences in the tested area – an example of such a case may be a tree and an adjacent road. The obtained resolution of the orthomosaic is always inferior to the resolution of the original images and in our research Ground Sample Distance, GSD=40 cm (Table 1). The obtained orthomosaics (Fig. 1), especially from later dates, clearly show the richness of crown colours in the trees resulting from the interspecific diversity (oak, pine) and phenological phases of individual trees (oak).

Classification of oaks based on the colours of their crowns. It was assumed that the changes in the colours of oak crowns, from green to brown, reflect the phenological state of trees, which is an expression of their preparation for winter rest. Although this is a continuous process, we decided to make observations at certain intervals because we expected that this will make the differences in the colours of trees more pronounced. We were also unable to perform the operation more often for organisational reasons (remote location of the test object, travel costs, etc.). The purpose of the visual interpretation of the photographs and classification of trees was to determine one general colour for the entire crown of the tree. Thus, crowns of individual oaks were classified into one of seven colours (Fig. 2): green (G), green-yellow (G/Y), yellow (Y), yellow-brown (Y/B1), brown (B1), brown with leaf loss (B2), trees with large leaf loss or without leaves (B3). We decided to perform visual classification due to differences in atmospheric conditions and the resulting radiometric differences visible when comparing photos from individual UAV flights. This effect is particularly visible in the images from October 22, as there were clouds present at the altitude at which the photos were taken. We also tried to take into account the phenomenon of deepening defoliation of tree crowns and the resulting exposure of lower layers of the stand, which was possible through the individual visual assessment of each tree and its spatial context

Table 1.

Parameters of photogrammetric flights and orthomosaics obtained

Parameter	8 Oct. 2016	22 Oct. 2016	30 Oct. 2016	6 Nov. 2016
Area covered [ha]	11.38	11.38	8.98	11.38
Distance flown [km]	4.24	4.24	3.11	4.01
Max speed [m s^{-1}]	9.7	11.6	5.0	5.0
Flight duration [minutes, seconds]	9 m 11 s	9 m 11 s	12 m 13 s	15 m 9 s
Altitude above terrain level, ATL [m]	115	115	115	115
Ground Sample Distance, GSD [m]	0.05	0.05	0.05	0.05
Number of images	111	111	83	112
Forward / side overlap [%]	80/80	80/80	80/80	80/80
Orthomosaic GSD [m]	0.40	0.40	0.40	0.40

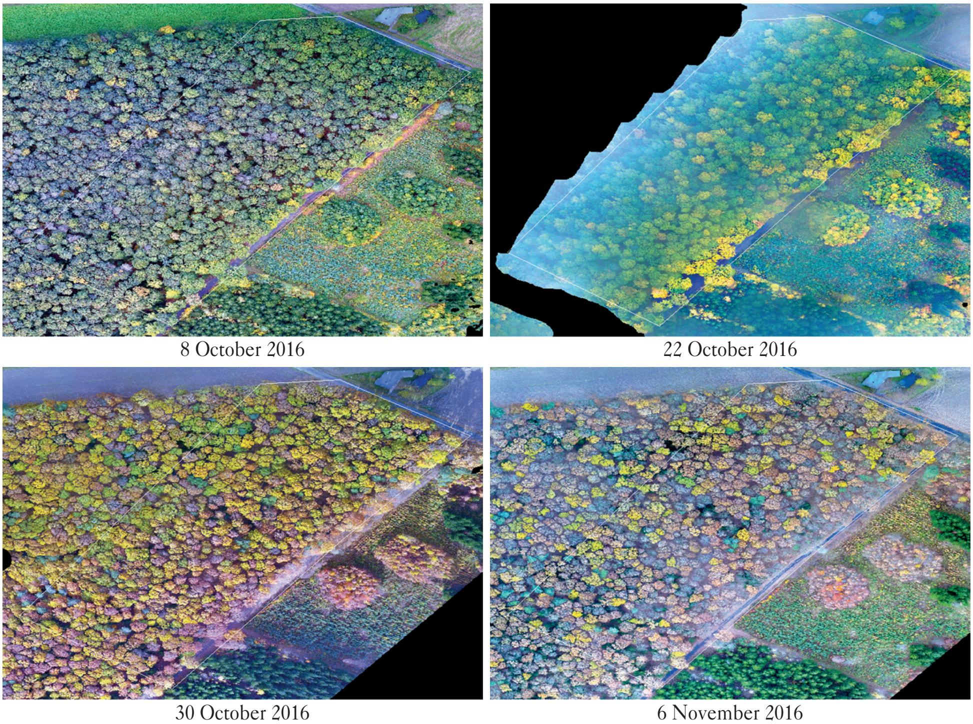

Fig. 1.

Orthomosaics composed of photographs taken on 8, 22, 30 October and 6 November 2016. Notice the progressive changes in the colors of the crowns. The photos from October 22 were taken in difficult weather conditions

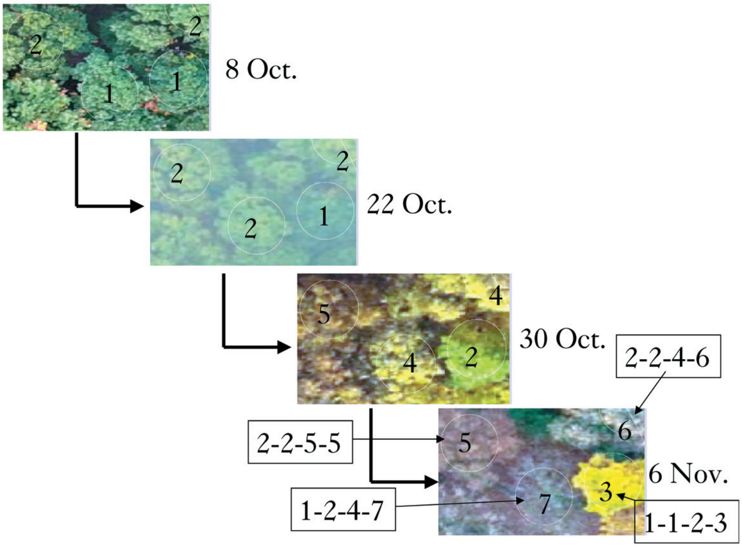

Fig. 2.

An example of classification of four oaks according to the colours of their crowns in subsequent dates of taking photos. For better readability of the drawing, letter markings have been replaced with numbers: 1=G, 2=G/Y, 3=Y, 4=Y/B1, 5=B1, 6=B2, 7=B3 performed by an interpreter. Due to the high variability in the quality of images and analysed objects (trees), we decided that the possible use of digital image classification methods, both supervised and unsupervised in both pixel (multispectral) and object-oriented modes, would be difficult and time-consuming. The currently proposed method, given the size of the object (several hundred trees), is acceptable in terms of labour intensity, although in the case of larger areas of research, machine methods should be considered. On the orthomosaics from October 8 and 22, the observer was able to distinguish oaks with crowns belonging to the first four colour classes G, G/Y, Y, and Y/B1. On October 30, classes B1 and B2 could be distinguished, while on November 6, large losses of the assimilation apparatus were observed in some trees, which was taken into account by introducing class B3. The observer first found and marked trees belonging to more easily recognisable colour classes, *i.e.* G, Y, B1, then assigned the remaining trees to intermediate colour classes, *i.e.* G/Y, Y/B1, and in the classification of images from the last two terms also to classes B2 and B3. A total of 599 oaks and 22 pines were identified in the stand. In further analyses, only oaks were considered. The division of oaks into different crown colour classes is shown in Figure 3.

The visual classification of tree crowns according to their colours is a subjective process, depending on the skills of the observer, as evidenced by, for example, the results obtained by Łoziński and Będkowski (2016) during the study of a group of observers. Image resolution, display settings, the observer's eyesight, the proportion of direct and scattered light, etc. are also important for the classification. Due to the closure of the tree crowns and the similarity of colours in adjacent trees, a different number of trees was identified each time. Therefore, to ensure that all trees were included in the study, they were first marked separately on orthomosaics from each date, and then the results were compared. Appropriate adjustments were made, which were facilitated by the fact that some trees at different times went to deeper phases of changing the colours of their crowns. However, it should be noted that omitting some trees (by merging their crowns) or, conversely dividing some crowns into two or more actually non-existent trees, is possible.

As shown in earlies studies of the dynamics of spring phenological changes (Będkowski, 2018), conclusions important for understanding the course of such phenomena can be drawn by tracing changes in phenological phases of individual trees (in our study we call them 'development

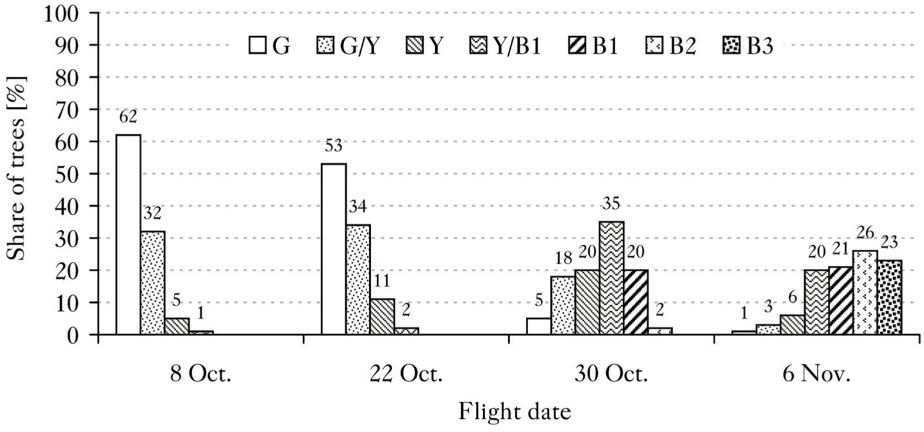

Fig. 3.
Share of oak trees according to their crown colours

paths'). The division of oaks into colour classes from subsequent classifications throughout the autumn allow for tracing the course of changes in the entire stand. We found how individual trees changed the colours of their crowns to determine whether patterns were visible. In particular, we were interested in whether the order of discoloration of trees found at the beginning is maintained throughout the observation period, which trees quickly go to winter dormancy and which keep their leaves green for a long time. In the chapter devoted to the discussion of the research results, we also draw attention to the potential impact of atmospheric conditions in the period between August and November 2016 – temperature and precipitation – comparing them with data from long-term observations of these meteorological factors.

Results

In the analysed period of 4 weeks, the share of oak crowns of different colours changed (Fig. 3). The rate of tree differentiation increased over time. The changes between October 8 and 22 are not large, only in later dates of observation was it possible to distinguish more classes.

In the autumn of 2016, sessile oaks changed their classes (crown colour) between dates, indicating that they were closer to winter dormancy, but it was also found that some trees (approx. 10%) did not change their classes. Theoretically, there should not be a situation where the tree returns to an earlier phase on a later date, *i.e.* it receives a lower class number. However, due to classification errors, these cases are not excluded. The theoretical and maximum, but completely unrealistic number of development paths, *i.e.* considering the possibility of the tree passing at subsequent stages to any level, is 4×4×6×7=672. If we assume that the only correct paths of development are those, where trees are included in the next term in the same or more advanced phenological phase of development, distinguished in subsequent dates 4, 4, 6 and 7 respectively, then in the collected material there should be at most 127 unique paths. We point here to the theoretically possible number of 'development paths' to which the number of paths that actually occurred in the analysed material can be referred, assuming that the fewer of them, the more it indicates the occurrence of a certain pattern (order) in the changes in the colours of trees. Then it is equally important how many trees develop along a given path. In our experiment, trees from the analysed collection (599 oaks) formed only 93 unique development paths (Fig. 4). Since it is impossible to clearly represent the development paths for all oaks, Figure 4a shows only the directions of transitions between individual classes, while Figures 4b,c,d shows the exact paths for selected groups of trees. Figure 4b shows the first ten most common development paths (Table 2), Figure 4c concerns trees that on the 8 October orthomosaic were classified as showing no or low symptoms of discolouring (G, G/Y or Y), while Fig. 4d shows the paths of development of trees that were classified as class B3 on the orthomosaic dated 6 November (trees with brown leaves and very high defoliation).

Table 2 presents paths arranged in descending order of the number of trees until the cumulative number of trees exceeding half the number of oaks in the stand is reached. In 42% of the trees, changes of crowns colours occurred in only 10 tracks, or unique development paths. This is important when comparing this result with the theoretical track numbers (672 or 127) calculated earlier and the number of unique tracks that were actually recorded (93). It is worth noting that in this part of the table, there are no questionable paths, *i.e.* trees classified to earlier phases of development of crown colours at further dates of observation. The first 5 paths cover $\frac{1}{4}$ and together with the next 3 paths as much as $\frac{1}{3}$ of the analysed trees. Most trees (38 individuals, 6.34%) went through phenological phases according to path 1-1-2-4.

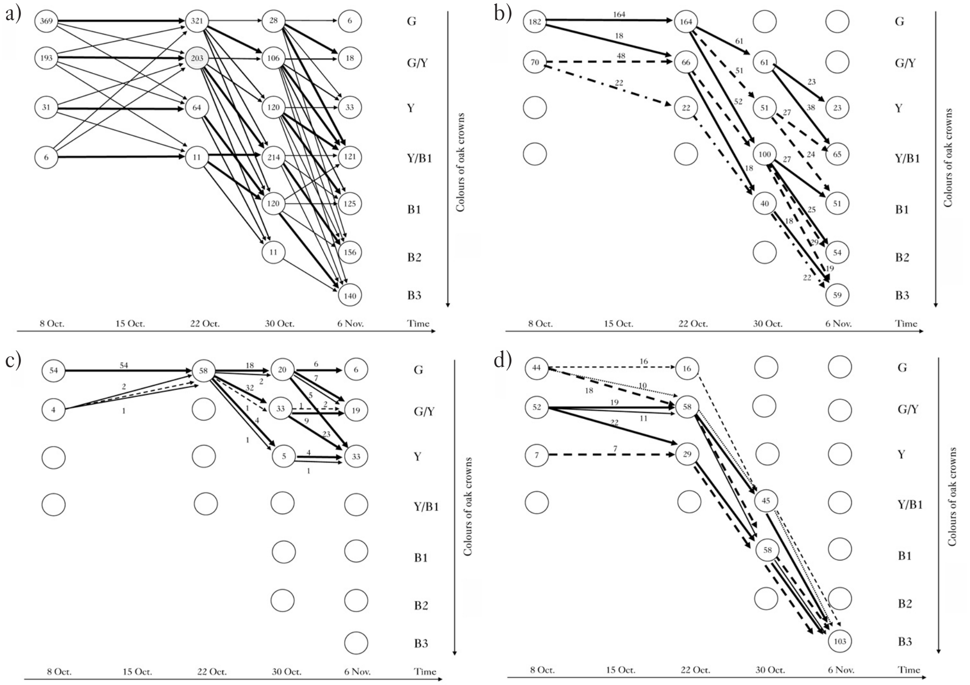

Fig. 4.

Paths of unique phenological development of oaks: (a) directions of transitions between colour classes – the bold line indicates a clearly higher abundance, (b) the first 10 most common paths that cover 42% of the trees surveyed, (c) all development paths of trees that ended development at level 1, 2 or 3 (G, G/Y, Y) on November 6, (d) paths of trees that completed development at level 7 on November 6 (B3) – for clarity, the most numerous paths are shown, i.e. for 103 out of 140 trees of this group. The numbers given in circles indicate the number of trees included in a given colour on a given day. The numbers above the arrows indicate the number of trees that have passed from one colour to another between consecutive days of observation. Fig. b, c, d indicates individual paths of tree groups with different lines, so it is possible to trace their course throughout the whole research period.

Table 2.

Oak development paths arranged according to the decreasing number of trees, until the cumulative number of over 50% of the population is reached (Fig. 4a)

Classification results (no. of crown colour)				No. of trees	No. of trees (cumulated)	
8 Oct.	22 Oct.	30 Oct.	6 Nov.	[pcs.]	[pcs.]	[%]
1	1	2	4	38	38	6.34
2	2	4	6	29	67	11.19
1	1	3	4	27	94	15.69
1	1	4	5	27	121	20.20
1	1	4	6	25	146	24.37
1	1	3	5	24	170	28.38
1	1	2	3	23	193	32.22
2	3	5	7	22	215	35.89
2	2	4	7	19	234	39.07
1	2	5	7	18	252	42.07
2	2	4	5	17	269	44.91
1	1	4	7	16	285	47.58
1	2	4	6	15	300	50.08

Discussion

Remote sensing methods never give complete certainty as to the correctness of the recognition of examined objects (their classification). In our research, there were at least three reasons that make it difficult to interpret the image:

1. At the beginning of the analysed period, only small differences in the colour of their crowns were visible in the trees, which made it difficult to decide on their manual classification.
2. The October 22 images were taken under very adverse lighting conditions, low cloud ceiling and haze. The orthomosaic from this date (Fig. 2) is of much worse quality compared to the others, there is also a clear gradient of brightness of the image in the southeast-northwest direction. Trees whose crowns are in fact similar colours may be mapped in photographs in colours so different, that they may be placed in different classes of phenological development. During the visual (manual) classification, such differences caused by image defects can be partially corrected by an experienced observer, but not completely, as shown by previous studies using a similar methodology (Wolinowski and Będkowski, 2015).
3. Trees with some discoloured leaves at the beginning of October could have shed them before the second registration, which resulted in a general change in the colour of their crowns and, as a result, a better assessment of their condition. The authors observed the described phenomenon in another species – common birch *Betula pendula* Roth. After a period of summer drought, the trees got rid of the yellowing leaves and the overall appearance of their crowns temporarily improved. Perhaps a similar mechanism also occurs in sessile oak? Leaf colour changes and defoliation are two processes that lead to the resulting colour of the crown observed in the photographs. Remote sensing now makes it possible to perform assessments of individual trees at different times. This creates a unique opportunity to keep track of changes.

The basic factors causing changes in the colour of tree leaves are temperature and precipitation. According to data for the Rogów weather station (approx. 2 km from the test site) in August and September 2016, two months before the period in which UAV flights were performed, rainfall was very small but increased in October (Fig. 5). Such a distribution of precipitation in the analysed months differs markedly from the long-term averages (Table 3). In August 2016, pre-

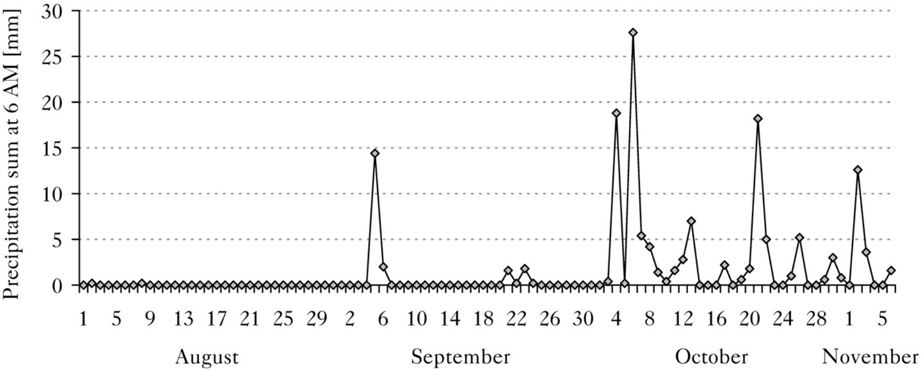

Fig. 5.
Precipitation between August 1 and November 6, 2016 (daily sums recorded at 6AM)

cipitation was the lowest in the entire multi-year period 1923-2016. The temperature (Fig. 6) was relatively high in August and September, then decreased at the beginning of October, with $t_{min}<0°C$ only occurring once in October, while such drops may not have occurred in the tree stand location and at the height of tree crowns. Average monthly temperatures in August and September 2016 were markedly higher than the long-term temperatures (Table 3).

The general picture of the condition of the stand, expressed by means of the participation of trees in individual phenological phases, changes slowly at first, but accelerates relatively quickly (Fig. 4a) and resembles the courses observed in spring (Będkowski, 2018). Finally, all trees would go to class 5 of leaf colour – brown oaks (B1). However, due to the parallel defoliation process, branches and trunks of trees are revealed in the picture, which results in colour changes so clear that it was possible to distinguish classes 6 and 7 (respectively B2, B3).

Figure 4b, which is related to Table 2, shows the first 10 most common paths and describes the development of as many as 42% of the trees studied. It is clearly visible that the division of trees into three classes outlined at the beginning of the period (8 October) generally determines their position at later dates (Fig. 4c,d). It can also be seen that some of the trees initially classified as class 1 – green oaks (G) quickly moved to more advanced stages of development, often ahead of others (Fig. 4a, paths 1-1-5-7 and 2-2-3-4). Trees classified at the beginning as class 3 (Y), mostly went to the most advanced stages of development (Fig. 4a, paths 3-3-5-7, 3-3-5-6, 3-3-5-5).

Table 3.

Temperature and precipitation during the study period compared with long-term averages (Chojnacka-Ożga, Ożga, 2015, 2018; Ożga, 2001)

		August	September	October	November
Temperature, t [°C], (1924-2016)	t_{min}	14.4	10.0	4.2	-2.4
	t_{mean}	17.0	12.9	7.8	3.0
	t_{max}	21.8	16.0	11.7	7.2
Temperature, t [°C], (2016)	t_{mean}	17.6	15.3	7.3	2.6
Precipitation, p [mm], (1923-2016)	p_{min}	0.4	2.2	0.0	1.1
	p_{mean}	69.6	47.1	39.6	42.6
	p_{max}	197.7	145.1	149.3	126.3
Precipitation, p [mm], (2016)	P_{sum}	0.4	20.2	108.2	45.4

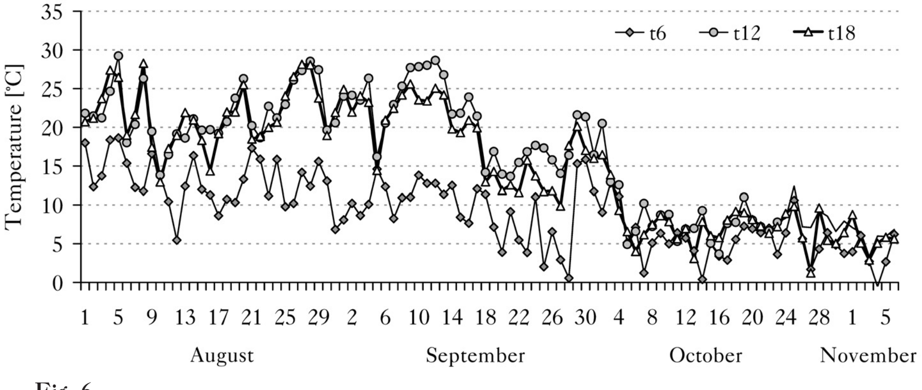

Fig. 6.

Air temperature between August 1 and November 6, 2016, recorded daily at 6 AM, 12 AM and 6 PM

The obtained results indicate dynamics of changes in the phenological state of trees, which may be invisible when we limit ourselves only to aggregate statistics for the stand, as in Fig. 3.

The most important result of the conducted research is that in autumn individual trees of sessile oak prepare for winter dormancy at different times and at different speeds, thus the order observed in autumn on a given day can change quickly, as there are trees in which the rate of colour change slows down or accelerates compared to other trees. In this respect, the dynamics of change is similar to the spring period (Będkowski, 2018). The trees that were the fastest to rest were those in which the earliest symptoms of changes in leaf colour were observed (Fig. 4a,d). However, about $^1/_{10}$ of trees maintained green (G) or slightly altered (G/Y, Y) foliage for a relatively long time (Fig. 4c). The obtained results also indicate that binding conclusions as to the course of the senescence process of individual trees based on one-off observations should be formulated very carefully, as cyclical observations showed that some trees overtook others and went into winter dormancy faster. In addition, results obtained just from one season may not be in compliance with potential outcomes from other years. Similar differences in crown colour may be observed in other species, but it is not known whether individual trees change the rate of change during the discoloration process. In further research, it is worth comparing spring and autumn observations to check whether there are forms with a long and short growing season in the stand and whether this feature is constant. Or are there other relationships between the dynamics of spring and autumn development, *e.g.* how do early and late flushing forms behave in autumn and what is the mechanism of these phenomena? It is also worth checking whether signs of trees preparing for winter dormancy can be noticed earlier, *i.e.* still in the summer, using spectrophotometric measurements or hyperspectral images.

Authors' contribution

Conceptualization and methodology – K.B., UAV-image acquisition and processing – P.S., image interpretation and classification – K.B., data processing – K.B., P.S., writing-review and editing – K.B., P.S.

Declaration of competing interest

The authors declare that they have no financial or personal conflicts with regard to the work reported in this paper.

Funding

The direct costs of the present research were financed from the authors' own funds. The results were analysed, and the present manuscript was prepared within the employing institutions of the authors.

References

Adamowski, W., 2008. Pierwszy w dostojności między drzewami, cz. II. *Matecznik Białowieski*, 1: 2-4.

Andrzejczyk, T., 2009. Dąb szypułkowy i bezszypułkowy. Warszawa: PWRiL, 301 pp.

Bacilieri, R., Ducousso, A., Kremer, A., 1995. Genetic, morphological, ecological and phenological differentiation between *Quercus petraea* (Matt.) Liebl. and *Quercus robur* L. in a mixed stand of Northwest France. *Silvae Genetica*, 44 (1): 1-10.

Barzdajn, W., 2000. Proweniencyjne doświadczenie z dębami (*Quercus robur* L. i *Q. petraea* [Matt.] Liebl.) z 1993 r. w nadleśnictwach Milicz i Oborniki Śląskie (Provenance trial of oaks (*Quercus robur* L. and *Q. petraea* [Matt.] Liebl.) from 1993 in Milicz and Oborniki Śląskie Forest Districts). *Sylwan*, 144 (12): 57-68.

Barzdajn, W., 2004. Proweniencyjna i rodowa zmienność wzrostu wysokości dębu szypułkowego (*Quercus robur* L.) na powierzchni porównawczej w Nadleśnictwie Bolesławiec, założonej w 1996 roku. [The provenance and family variability in pedunculate oak (*Quercus robur* L.) height on the comparative plot established in 1996 in Bolesławiec Forest District]. *Sylwan*, 148 (10): 3-12. DOI: https://doi.org/10.26202/sylwan.2004020.

Będkowski, K., 2018. Dynamika wiosennych zjawisk fenologicznych w drzewostanie dębu bezszypułkowego (*Quercus petraea* [Matt.] Liebl.). [Dynamics of the spring phenological phenomena in the sessile oak (*Quercus petraea* [Matt.] Liebl.) stand]. *Sylwan*, 162 (12): 998-1006. DOI: https://doi.org/10.26202/sylwan.2018106.

Będkowski, K., Stereńczak, K., 2013. Sessile oak (*Quercus petraea* (Mattuschka) Liebl.) trees variability according to an analysis of multispectral images taken from UAV – first results. *Ecological Questions*, 17: 25-33. DOI: https://doi.org/10.12775/ecoq-2013-0013.

Boratyński, A., 1994. Zarys systematyki dębów (Outline of Oak Taxonomy). *Sylwan*, 188 (10): 73-88.

Boratyński, A., Filipiak, M., Kosiński, P., Sekieta, M., 1997. Występowanie dębu szypułkowego (*Quercus robur* L.), bezszypułkowego (*Quercus petraea* (Matt.) Liebl.) i ich mieszańców (*Quercus* × *rosacea* Bechst.) w wyłączonych drzewostanach nasiennych RDLP Gdańsk. [Occurence of Pedunculate Oak (*Quercus robur* L.) and Sessile Oak (*Quercus petraea* (Matt.) Liebl.) and their Hybrids (*Quercus* × *rosacea* Bechst.) in Selected Seed Stands in the RDSF Gdańsk Area]. *Sylwan*, 191 (5): 41-49.

Boratyński, A., Sztajnborn, K., 2001. Dębowe drzewostany nasienne w Nadleśnictwie Runowo (The oak-seeds stands of Runowo Forest District). *Sylwan*, 145 (3): 43-51.

Boyer, M., Miller, J., Belanger, M., Hare, E, Jiyou, W., 1988. Senescence and spectral reflectance in leaves of Northern Pin Oak (*Quercus palustris* Muenchh). *Remote Sensing of Environment*, 25: 71-87. DOI: https://doi.org/10.1016/0034-4257(88)90042-9.

Chmielewski, F.M., Rötzer, T., 2001. Response of tree phenology to climate change across Europe. *Agricultural and Forest Meteorology*, 108 (2): 101-112. DOI: https://doi.org/10.1016/S0168-1923(01)00233-7.

Chojnacka-Ożga, L., Ożga, W., 2015. Zmiany opadów atmosferycznych w Lasach Doświadczalnych SGGW w Rogowie w latach 1923-2014. In: H. Lorenc, Z. Ustrnul, eds. *Klimat a społeczeństwo i gospodarka*. Warszawa: Polskie Towarzystwo Geofizyczne, pp. 71-82.

Chojnacka-Ożga, L., Ożga, W., 2018. Air temperature anomalies in experimental forests in Rogów in 1924-2015. *Leśne Prace Badawcze / Forest Research Papers*, 79 (1): 37-44. DOI: https://doi.org/10.2478/frp-2018-0005.

Chojnacka-Ożga, L., Ożga, W., 2023. Charakterystyka okresu wegetacyjnego w Lasach Doświadczalnych SGGW w Rogowie w latach 1951-2020. (Characteristics of the growing season in the Experimental Forests of the Warsaw University of Life Sciences in Rogów in the years 1951-2020). *Prace Geograficzne*, 170: 83-97. DOI: https://doi.org/10.4467/20833113PG.23.003.17491.

Crawley, M.J., Akhteruzzaman, M., 1988. Individual variation in the phenology of oak trees and its consequences for herbivorous insects. *Functional Ecology*, 2 (3): 409-415. DOI: https://doi.org/10.2307/2389414.

Davi, H., Gillmann, M., Ibanez, T., Cailleret, M., Bontemps, A., Fady, B., Lefèvre, F., 2011. Diversity of leaf unfolding dynamics among tree species. New insights from a study along an altitudinal gradient. *Agricultural and Forest Meteorology*, 151 (12): 1504-1513. DOI: https://doi.org/10.1016/j.agrformet.2011.06.008.

Ducousso, A., Guyon, J.P., Krémer, A., 1996. Latitudinal and altitudinal variation of bud burst in western populations of sessile oak (*Quercus petraea* (Matt) Liebl). *Annals of Forest Science*, 53: 775-782. DOI: https://doi.org/10.1051/forest:19960253.

Ekholm, A., Tack, A.J.M., Bolmgren, K., Roslin, T., 2019. The forgotten season: The impact of autumn phenology on a specialist insect herbivore community on oak. *Ecological Entomology*, 44 (3): 425-435. DOI: https://doi.org/10.1111/een.12719.

Estrella, N., Menzel, A., 2006. Responses of leaf colouring in four deciduous tree species to climate and weather in Germany. *Climate Research*, 32: 253-267. DOI: https://doi.org/10.3354/cr032253.

Fenner, M., 1998. The phenology of growth and reproduction in plants. *Perspectives in Plant Ecology, Evolution and Systematics*, 1 (1): 78-91. DOI: https://doi.org/10.1078/1433-8319-00053.

Fijałkowski, D., 1968a. Zmienność dębów szypułkowego (*Quercus robur* L.) i bezszypułkowego (*Quercus sessilis* Ehrh.) w lasach Lubelszczyzny. [Variation of pedunculate (*Quercus robur* L.) and durmast (*Quercus sessilis* Ehrh.) oaks in forests of Lublin province]. *Sylwan*, 112 (12): 41-47.

Fijałkowski, D., 1968b. Badania nad okresami rozwijania się i zrzucania liści u dębu szypułkowego *Quercus robur* L. (Studies of periods of developing and falling down of leaves in *Quercus robur* L.). *Annales Universitatis Mariae Curie-Skłodowska Lublin – Polonia*, 22 (13): 203-212.

Fober, H., Rożkowski, R., 2006. Ocena polskich ras dębu szypułkowego (*Quercus robur* L.) i bezszypułkowego (*Q. petraea* [Matt.] Liebl.) testowanych w doświadczeniu proweniencyjnym w Kórniku. (An assessment of the Polish races of pedunculate (*Quercus robur* L.) and sessile (*Q. petraea* [Matt.] Liebl.) oaks tested in a provenance trial in Kórnik). *Sylwan*, 150 (11): 3-13. DOI: https://doi.org/10.26202/sylwan.2006012.

Hernik, I., 1973. Fenologiczne formy dębu szypułkowego (Phenological forms of the English oak). *Sylwan*, 117 (7): 61-69.

Kadomatsu, M., 1997. Differences in phenology of *Quercus* collected from Northeastern China, Eastern Hokkaido and Western Honshu. *Research Bulletin of the Hokkaido University Forests*, 54 (2): 188-201.

Keskitalo, J., Bergquist, G., Gardeström, P., Jansson, S., 2005. A cellular timetable of autumn senescence. *Plant Physiology*, 139: 1635-1648. DOI: https://doi.org/10.1104/pp.105.066845.

Kiełczewski, B., 1962. Fenologia na usługach ochrony lasu. (Phenology on the service of the forest protection). *Sylwan*, 106 (2): 33-38.

Kleinschmit, J., 1993. Intraspecific variation of growth and adaptive traits in European Oak species. *Annals of Forest Science*, 50: 166-185. DOI: https://doi.org/10.1051/forest:19930716.

Kolář, T., Giagli, K., Trnka, M., Bednářová, E., Vavrčík, H., Rybníček, M., 2016. Response of the leaf phenology and tree-ring width of European beech to climate variability. *Silva Fennica*, 50 (2): 1520. DOI: https://doi.org/10.14214/sf.1520.

Kot, I., Rubinowska, K., Michałek, W., 2018. Changes in chlorophyll fluorescence and pigments composition in oak leaves with galls of two cynipid species (Hymenoptera, Cynipidae). *Acta Scientiarum Polonorum Hortorum Cultus*, 17 (6): 147-157. DOI: https://doi.org/10.24326/asphc.2018.6.15.

Kozłowska, M., ed. 2007. Fizjologia roślin: od teorii do nauk stosowanych. Poznań: PWRiL, 544 pp.

Lechowicz, M.J., 1984. Why do temperate deciduous trees leaf out at different times? Adaptation and ecology of forest communities. *American Naturalist*, 124 (6): 821-842. DOI: https://www.journals.uchicago.edu/doi/10.1086/284319.

Lim, P.O., Kim, H.J., Nam, H.G., 2007. Leaf senescence. *Annual Review of Plant Biology*, 58: 115-136. DOI: https://doi.org/10.1146/annurev.arplant.57.032905.105316.

Lisein, J., Michez, A., Claessens, H., Lejeune, P., 2015. Discrimination of deciduous tree species from time series of unmanned aerial system imagery. *PLoS ONE*, 10 (11): e0141006. DOI: https://doi.org/10.1371/journal.pone.0141006.

Łoziński, A., Będkowski, K., 2016. Rozpoznawanie jesiennych faz fenologicznych dębu bezszypułkowego (*Quercus petraea* Liebl.) na ortomozaikach zdjęć lotniczych uzyskanych z wykorzystaniem drona. [Monitoring of sessile oak (*Quercus petraea* Liebl.) autumn phenology using orthomosaics made on a basis of aerial images acquired with drone]. *Teledetekcja Środowiska*, 55: 5-14.

Markowski, R., 1993. Udział dębu szypułkowego (*Quercus robur* L.) i bezszypułkowego (*Quercus petraea* (Mattuschka) Liebl.) w zbiorowiskach leśnych Pobrzeża i Pojezierza Kaszubskiego. [The share of pedunculate oak (*Quercus robur* L.) and sessile oak (*Quercus petraea* (Mattuschka) Liebl.) in forest communities of the Kashubian Coastal Zone and the Kashubian Lakeland). *Sylwan*, 137 (12): 85-93.

Merzlyak, M.N., Gitelson, A.A., Chivkunova, O.B., Rakitin, V.Y., 1999. Non-destructive optical detection of pigment changes during leaf senescence and fruit ripening. *Physiologia Plantarum*, 106: 135-141. DOI: https://doi.org/10.1034/j.1399-3054.1999.106119.x.

Olędzki, J.R., 1993. Badania zróżnicowania własności optyczno-spektralnych środowiska geograficznego. (Studies on differentiation of optical spectral properties of geographic environment). *Teledetekcja Środowiska*, 23: 7-35.

Ożga, W., 2001. Zmienność czasowa opadów atmosferycznych w Lasach Doświadczalnych SGGW w Rogowie w latach 1923-2000. (Time variation of atmospheric precipitation in the Exprimental Forests SGGW in Rogów in the years 1923-2000). *Sylwan*, 145 (10): 53-60.

Polgar, C.A., Primack, R.B., 2011. Leaf-out phenology of temperate woody plants: from trees to ecosystems. *New Phytologist*, 191: 926-941. DOI: https://doi.org/10.1111/j.1469-8137.2011.03803.x.

Samek, T., 1988. Tworzenie drewna a rozwój i trwałość ulistnienia u *Quercus robur* L. Warszawa: Katedra Botaniki Leśnej Wydziału Leśnego SGGW-AR (rozprawa doktorska).

Schlarbaum, S.E., Bagley, W.T., 1981. Genetic variation of *Quercus rubra* L., Northern Red Oak. *Silvae Genetica*, 30 (2-3): 50-56.

Sims, D.A., Gamon, J.A., 2002. Relationships between leaf pigment content and spectral reflectance across a wide range of species, leaf structures and developmental stages. *Remote Sensing of Environment*, 81: 2-3: 337-354. DOI: https://doi.org/10.1016/S0034-4257(02)00010-X.

Soto, G.E., Pérez-Hernández, C.G., Hahn, I.J., Rodewald, A.D., Vergara, P.M., 2017. Tree senescence as a direct measure of habitat quality: Linking red-edge Vegetation Indices to space use by Magellanic woodpeckers. *Remote Sensing of Environment*, 193: 1-10. DOI: https://doi.org/10.1016/j.rse.2017.02.018.

Škvareninová, J., Domčeková, D., Snopková, Z., Škvarenina, J., Šiška, B., 2008. Phenology of pedunculate oak (*Quercus robur* L.) in the Zvolen basin, in dependence on bio-meteorological factors. *Folia Oecologica*, 35 (1): 40-47.

Trąba, C., Wolański, P., Rogut, K., 2012. Fenologia i fenologiczne pory roku. *Aura*, 5: 8-10.

Vitasse, Y., François, C., Dolpierre, N., Dufrêne, E., Kremer, A., Chuine, I., Delzon, S., 2011. Assessing the effects of climate change on the phenology of European temperate trees. *Agricultural and Forest Meteorology*, 151 (7): 969-980. DOI: https://doi.org/10.1016/j.agrformet.2011.03.003.

Waddell, K.J., Fox, C.W., White, K.D., 2001. Leaf abscission phenology of a scrub oak: Consequences for growth and survivorship of a leaf mining beetle. *Oecologia*, 127, 251-258.

Weidler, S.K., Sivanpillai, R., 2020. Sunbathed aspen grow to show how sunlight influences aspen leaf changes in the autumn season. *The International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences*, 45 (2): 105-110. DOI: https://doi.org/10.5194/isprs-archives-XLIV-M-2-2020-105-2020.

Wesołowski, T., Rowiński, P., 2006. Timing of bud burst and tree-leaf development in a multispecies temperate forest. *Forest Ecology and Management*, 237: 387-393. DOI: https://doi.org/10.1016/j.foreco.2006.09.061.

Włoczewski, T., 1953. Przejawy zmienności drzew w życiu lasu. Materiały konferencji agrobiologicznej leśników. Rogów, 9-13 września 1952 r. Warszawa: PWRiL.

Wolinowski, P., Będkowski, K., 2015. Ocena stanu zdrowotnego świerka pospolitego (*Picea abies* Karst.) na podstawie zdjęć lotniczych wykonanych z niskiej wysokości w okresie intensywnego wiosennego wzrostu drzew. [Assessment of Norway spruce (*Picea abies* Karst.) health based on low altitude aerial images acquired in the spring, the period of intensive trees growth]. *Teledetekcja Środowiska,* 53: 5-14.

Zaręba, R., 1952. Początek wiosny w Polsce środkowej i wschodniej na podstawie obserwacji leśno-fenologicznych rozwoju liści leszczyny i brzozy gruczołkowatej z lat 1934-37. *Sylwan,* 96 (3): 361-370.

Zaręba, R., 1962. O potrzebie rozróżniania obydwu gatunków naszych dębów w gospodarce leśnej. *Las Polski,* 8: 16-17.

Zaręba, R., 1993. Dąb bezszypułkowy i jego znaczenie w obecnych warunkach. *Las Polski,* 17: 8-10.

STRESZCZENIE

Dynamika jesiennych zmian barw koron drzew w drzewostanie dębu bezszypułkowego na podstawie serii czasowej niskopułapowych zdjęć lotniczych

Na podstawie serii czasowej zdjęć lotniczych wykonanych jesienią 2016 r. za pomocą bezzałogowego systemu powietrznego (tab. 1) badano przebieg zjawisk fenologicznych w drzewostanie dębu bezszypułkowego położonego w centralnej Polsce. Zdjęcia zostały przetworzone do tzw. ortomozaik RGB (ryc. 1). W terminach rejestracji zdjęć wystąpiły odmienne warunki meteorologiczne: 30 października zdjęcia wykonano przy pełnym bezpośrednim oświetleniu słonecznym, 8 października i 6 listopada przy niskim pułapie chmur, a 22 października obecność chmur i mgły wyraźnie wpłynęła na jakość uzyskanych obrazów. Przyjęto, że obserwowane na ortomozaikach barwy koron są widocznym objawem stanu przygotowania drzew do spoczynku zimowego. Ze względu na dużą zmienność jakości obrazów klasyfikację drzew przeprowadzono na podstawie wizualnej oceny barw. Dęby podzielono na 7 klas: z koronami zielonymi (G), zielonożółtymi (G/Y), żółtymi (Y), żółtobrązowymi (Y/B1), brązowymi (B1), brązowymi z ubytkiem aparatu asymilacyjnego (B2) oraz brązowymi z dużym ubytkiem aparatu asymilacyjnego (B3) (ryc. 2, 3). Obserwator wyróżniał najpierw korony z barwami łatwiejszymi do rozpoznania (G, Y, B1), następnie decydował o zaklasyfikowaniu pozostałych drzew. Kontrolował również, czy wszystkie drzewa (599 dębów) zostały zaklasyfikowane na ortomozaikach z każdego terminu. Wyróżnianie koron indywidualnych drzew było często ułatwione dzięki odmiennym barwom koron sąsiadujących ze sobą drzew.

Analizowano udział w drzewostanie drzew z koronami o różnych barwach (ryc. 3), a także przebieg zmian barw każdego z dębów w całym okresie obserwacji. Stwierdzono, że jesienią poszczególne drzewa dębu bezszypułkowego w różnych terminach i w różnym tempie przygotowują się do spoczynku zimowego. Większość drzew przechodziła podobne cykle przemian, co wyraża się w tym, że można je opisać za pomocą kilku tzw. indywidualnych ścieżek rozwoju (tab. 2; ryc. 4a, 4b). Najszybciej do spoczynku przechodziły te drzewa, u których najwcześniej zaobserwowano objawy zmian barw liści (ryc. 4d). Tym samym już we wczesnej fazie procesu przemiany barw koron można wskazać drzewa, u których stan spoczynku zimowego zostanie osiągnięty najszybciej. Około $^1/_{10}$ drzew stosunkowo długo utrzymywała zielone (G) lub nieznacznie zmienione (G/Y, Y) ulistnienie (ryc. 4c).

W okresie objętym badaniami temperatura powietrza po ciepłym sierpniu i wrześniu gwałtownie obniżyła się na początku października, po czym dalej stopniowo się obniżała, lecz poza jednym wyjątkiem nie spadła poniżej zera (ryc. 5). Opady w sierpniu i wrześniu były bardzo niskie (ryc. 6). Warto też zauważyć, że opady w sierpniu 2016 r. były najniższe z zarejestrowanych w całym wieloleciu (tab. 3). Taki przebieg temperatury i opadów mógł mieć wpływ na

zaobserwowane stopniowe zmiany barw liści dębów, w tym utrzymanie zielonych liści u części drzew aż do listopada.

Z przeprowadzonych badań wynika wniosek, że barwy koron, jakie można zaobserwować w danym momencie w drzewostanie, nie zawsze są dobrym wskaźnikiem kolejności przechodzenia drzew do spoczynku zimowego. Niektóre drzewa, wyprzedzając pozostałe, w efekcie szybciej przechodziły do spoczynku zimowego, niż można było się tego spodziewać na podstawie wcześniejszych obserwacji.