

THE IMPACT OF GLOBAL WARMING ON THE VEGETATION SEASON IN POLAND IN 1961-2020

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Abstract

This article provides an analysis of the variability of the vegetation period (VP) and of the intensive vegetation period (IVP) in Poland in the years 1961-2020. Using average monthly values of air temperature from 55 weather stations in Poland, the VP and IVP onset- and end-dates were determined. A substantial spatial variability was found in the timing of the onset and termination of the VP and IVP in Poland. A statistically significant trend towards a longer vegetation period was also observed. The considerable extension of the VP and IVP affects the environment and human activities.

Keywords

vegetation period • intensive vegetation period • climate change • Poland

Introduction

Changes in the start- and end-dates and the duration of the thermal seasons are a consequence of the continuing global warming (Czernecki & Miętus, 2017; Kejna & Pospieszńska, 2023), which also affects the vegetation season (Linderholm, 2006; Szyga-Pluta et al., 2022). According to the Sixth Assessment Report IPCC (2021) the global air temperature in the decade of 2011-20 was 1.1°C

higher compared with the pre-industrial era (1850-1900).

The growing season, or the vegetation period (VP), is the part of the year when the average diurnal air temperature exceeds 5°C (Słownik Meteorologiczny, 2003). In such thermal conditions, plants begin and finish vegetation. In the Polish literature references, the term was introduced by Romuald Merecki in 1914 (Olszewski & Żmudzka, 2000). A similar criterion was used by Jones and Briffa (1995),

Carter (1998), Frich et al. (2002), Barichivich et al. (2013), Cui et al. (2018) and Wu et al. (2021). The sums of effective temperatures exceeding the threshold value affect the developmental phases of plants (Menzel et al., 2003; Kopeć, 2009). The intensive vegetation period (IVP) is also often identified as the one in which the air temperature remains above 10°C (Szejewski et al., 2008; Kopeć, 2009; Źarski et al., 2012; Źmudzka, 2012; Tomczyk & Szyga-Pluta, 2018). The growing becomes more intense when the air temperature rises above 10°C. This temperature is decisive for the vegetative and rapid generative growth of trees (Rubner, 1960). The forest vegetation season begins (Duro, 2010).

Under conditions of global warming, the VP starts earlier and ends later in many regions of the world (Carter, 1998; Jaak & Rein, 2000; Ahas et al., 2000; Chmielewski & Rötzer, 2002; Jaagus et al., 2003; Linderholm, 2006; Schwartz et al., 2006; Walther & Linderholm, 2006; Song et al., 2009; Barichivich et al., 2013; Liu et al., 2016; Park et al., 2016; Cui et al., 2017; Středová et al., 2017; Craig & Allan, 2021; Szyga-Pluta et al., 2023). Plant growing conditions change, climate and vegetation zones shift towards the poles (Beck et al., 2018) and phenophases are altered (Menzel & Fabian, 1999; Chmielewski & Rötzer, 2001; Menzel et al., 2003; Chmielewski et al., 2004).

In Poland, research into thermal seasons and the vegetation period has been conducted for over 100 years. As early as at the start of the 20th century, Romer (1906) and Merecki (1915) identified six thermal seasons as characteristic of the transitional climate of Poland. The vegetation season has also been the subject of works, and its spatial and temporal variability has been analysed in numerous scientific publications. Maps showing the spatial distribution of the VP in Poland can be found in various works and atlases: Bartnicki, 1948; Molga, 1980; Olszewski & Źmudzka 2000; Lorenc (2025); Nieróbca et al., (2013), Tomczyk & Bednorz (2022).

As in many other parts of the world (Linderholm, 2006; Linderholm et al., 2008; Wo et al., 2021), so too in Poland, major changes in the

onset of the vegetation period have occurred in recent decades (Źmudzka & Dobrowolska, 2001; Skowera & Kopeć, 2008; Kijowska, 2010; Bochenek et al., 2013; Nieróbca et al., 2013; Źmudzka, 2012; Kružel et al., 2015; Tylkowski, 2015; Graczyk & Kundzewicz, 2016; Tomczyk & Szyga-Pluta, 2016; Chojnacka-Ożga & Ożga, 2018; Szyga-Pluta & Tomczyk, 2019; Radzka, 2021). The rate of these changes has accelerated dramatically because of global warming (Szyga-Pluta et al., 2023). Nevertheless, despite the extended duration of the vegetation season, Poland is still affected by late ground frost (in May and June), which harms crops (Kozmiński et al., 2021).

This article aims to analyse the spatial distribution of the start- and end-dates and duration of the VP and IVP in Poland in the years 1961-2020. The variability and trends related to the onset of the two periods are also investigated. The article presents new data on the vegetation season in Poland, on rapidly progressing changes related to global warming. The issues are relevant in view of environmental changes and their implications for growing crops.

Research area and methods

The study used average monthly air temperature values from 1961-2020 obtained from 55 weather stations in Poland (Fig. 1). The data is available on the website of the Institute of Meteorology and Water Management, National Research Institute (IMGW PIB). The source data was described in the article by Kejna & Pospieszńska (2023).

To determine the dates of the beginning and end of the vegetation period and the thermal seasons, graphical or mathematical methods are used (Romer, 1906; Merecki, 1915; Huculak & Makowiec, 1977; Bartoszek et al., 2012; Kępińska-Kasprzak & Mager, 2015).

In this study, a mathematical formulas developed by Gumiński (1950) are used.

For an increase in temperature:

$$x = \frac{t_p - t_1}{t_2 - t_1} \cdot n$$

For a decrease in temperature:

$$x = \frac{t_1 - t_p}{t_1 - t_2} \cdot n$$

where:

t_1 – mean monthly temperature in the month preceding the crossing of the threshold value,

t_2 – mean monthly temperature in the following month,

t_p – threshold value (5°C or 10°C),

n – number of days in the previous month,

x – number of days to be added to the 15th day of the previous month.

These formulas work well for multi-year average temperature values. In the case of individual years, the temperature sometimes tends to cross the threshold values. In this study, instances of such crossings were only

observed in a few years and at a few stations; the threshold temperatures of 5°C or 10°C were crossed twice. Accordingly, the number of days in the periods with temperatures above and below the thermal thresholds were counted as proposed by Samborski & Bednarczuk (2009). The method was described in detail in an article by Kejna & Pospieszyska (2023).

A proprietary R script was used to calculate the beginning and end dates of the VP and IVP. The spatial analysis of the dates marking the onset and termination of a vegetation season was based on the kriging method (Childs, 2004). The t-Student test was used to assess the statistical significance of the obtained linear trends for the start, end and duration dates. The significance level was set at 0.05.

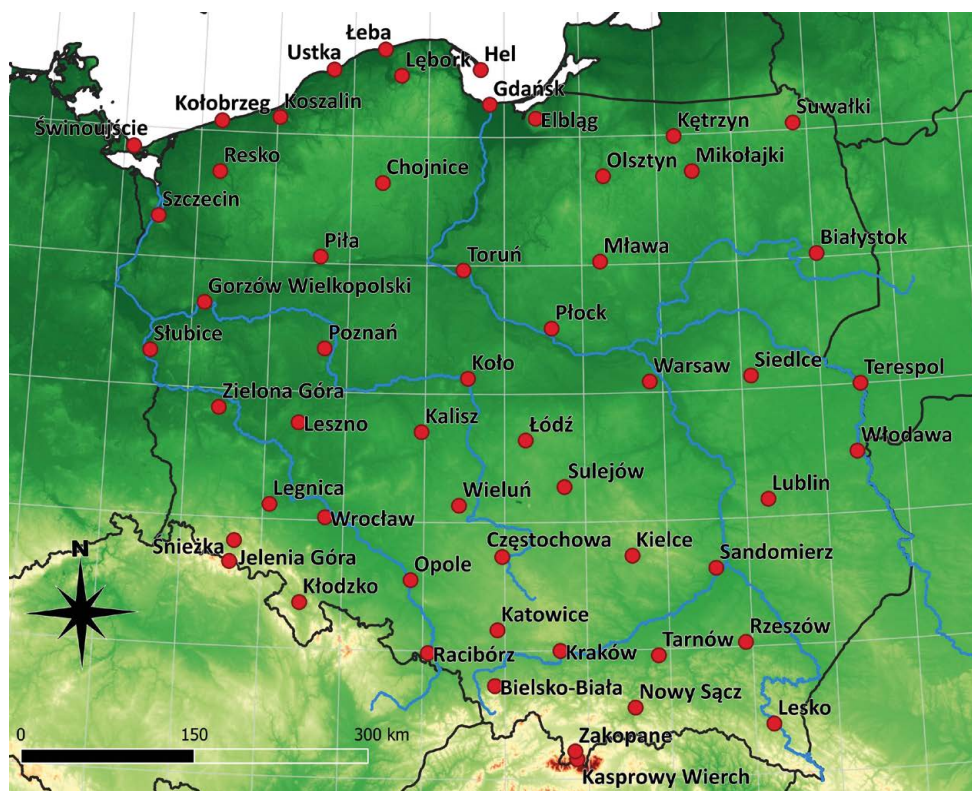


Figure 1. Location of Institute of Meteorology and Water Management stations used in the study

Results

Vegetation period

Spatial distribution of the onset and duration of the vegetation period

In 1961-2020 in Poland, the vegetation period started at the end of March and the beginning of April (Tab. 1, Fig. 2). The onset came

earliest in the west of the country (Słubice, 22 March; Szczecin, 23 March) and then gradually moved towards central and eastern Poland (Terespol and Włodawa, 30 March). A distinct delay was observed at the Baltic Sea (Hel, 7 April) and in the country's north-east (Suwałki, 7 April). In the mountains, the onset of the VP was delayed with altitude

Table. 1. Mean beginning and end dates and duration of vegetation period and intensive vegetation period in selected stations in Poland

Station	Period	Vegetation period (> 5°C)			Intensive vegetation period (> 10°C)		
		Start	End	Duration	Start	End	Duration
Świnoujście	1961-1990	3.04	12.11	224	07.05	12.10	158
	1991-2020	24.03	16.11	238	30.04	13.10	166
	1961-2020	28.03	13.11	231	04.05	13.10	162
Gdańsk	1961-1990	6.04	7.11	216	07.05	06.10	152
	1991-2020	2.04	5.11	218	03.05	03.10	153
	1961-2020	4.04	6.11	217	05.05	04.10	152
Suwałki	1961-1990	11.04	25.10	198	05.05	25.09	143
	1991-2020	3.04	28.10	209	30.04	29.09	152
	1961-2020	7.04	27.10	204	03.05	27.09	147
Słubice	1961-1990	25.03	10.11	231	27.04	10.10	166
	1991-2020	19.03	12.11	239	18.04	11.10	176
	1961-2020	22.03	11.11	235	23.04	10.10	170
Warszawa	1961-1990	31.03	3.11	218	27.04	05.10	161
	1991-2020	24.03	7.11	229	20.04	08.10	171
	1961-2020	27.03	5.11	224	23.04	06.10	166
Terespol	1961-1990	2.04	31.10	213	27.04	02.10	158
	1991-2020	27.03	3.11	222	21.04	04.10	166
	1961-2020	30.03	2.11	218	24.04	03.10	162
Wrocław	1961-1990	26.03	8.11	228	26.04	08.10	165
	1991-2020	19.03	13.11	240	17.04	13.10	179
	1961-2020	22.03	10.11	234	22.04	11.10	172
Kraków	1961-1990	29.03	4.11	221	27.04	06.10	162
	1991-2020	23.03	7.11	230	19.04	08.10	172
	1961-2020	26.03	5.11	225	24.04	07.10	166
Lublin	1961-1990	2.04	1.11	214	28.04	02.10	157
	1991-2020	28.03	3.11	221	23.04	05.10	165
	1961-2020	30.03	2.11	218	26.04	03.10	160
Zakopane	1961-1990	17.04	22.10	189	20.05	16.09	119
	1991-2020	8.04	25.10	201	11.05	21.09	133
	1961-2020	12.04	23.10	195	14.05	19.09	128
Śnieżka	1961-1990	30.05	19.09	113	.	.	.
	1991-2020	20.05	21.09	125	.	.	.
	1961-2020	25.05	20.09	119	.	.	.
Kasprowy Wierch	1961-1990	12.06	6.09	87	.	.	.
	1991-2020	31.05	11.09	104	.	.	.
	1961-2020	6.06	10.09	97	.	.	.

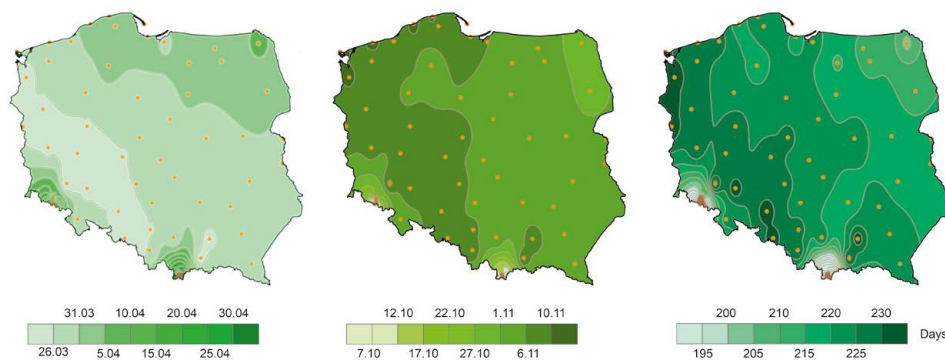


Figure 2. Average dates of onset (left map), termination (middle map) and duration (right map) of the vegetation period in Poland in 1961-2020

(Mt. Śnieżka, 25 May; Mt. Kasprowy Wierch, 6 June). The VP ended earliest in the mountains (Kasprowy Wierch, 10 September; Śnieżka, 20 September) and in the north-east of the country (Suwałki, 27 October). The period ends progressively later towards the west, e.g., on 5 November in Warsaw, 8 November in Poznań, and 11 November in Słubice. The vegetation season ends even later at the seaside (Hel, 16 November).

In 1961-2020, the VP in Poland lasted on average from 204 days in the east (Suwałki) to more than 230 days in the west (Legnica, 237 days; Słubice and Szczecin, 235 days) and the south (Opole, 235 days; Racibórz, 234 days; Tarnów, 233 days). Shorter vegetation period occurred in the north, especially on the Baltic coast (Gdańsk and Ustka, 217 days). The VP is very short in the mountains and lasted 119 days on Śnieżka and only 97 days on Kasprowy Wierch.

Variability of the onset and duration of the vegetation period

The Polish climate is characterised by substantial year-on-year variability of meteorological conditions (Woś, 2010; Kożuchowski, 2011). This affects the start- and end-dates and the duration of the vegetation period VP (Fig. 3). The differences between the earliest and the latest onset of the VP at individual stations were 90-100 days. For example, in Hel on the Baltic coast, the VP started as early as 16 January or as late as 25 April (Fig. 4).

The onset of the VP was more stable in the east of Poland: e.g. in Suwałki, the VP started between 17 March and 20 April, so the time frame spanned 34 days. In the mountains, the vegetation season came late and the difference in the dates of its onset reached 75 days on Kasprowy Wierch and 67 days on Śnieżka. The considerable variability of the onset of VP was validated by the standard deviation value, which ranged from 8.4 days in Suwałki to 18.1 days in Szczecin.

The end-dates of the VP also varied over the analysed period: e.g. in the west of the country, in Słubice, the VP ended between 26 October and 19 January of the following year (85 days) (Fig. 4). The smallest differences in the dates of the end of VP were found in the east and centre of Poland (Sulejów, 23 October – 25 November). The standard deviation of end dates ranged from 8.5 days in Kraków to 13.6 days in Słubice and 14.1 on Śnieżka.

The duration of the VP can vary among years (Fig. 4). The most significant differences in the duration of VP occurred in the west of the country (Gorzów Wielkopolski, 187-317 days, i.e. a difference of 130 days) and in the mountains (Kasprowy Wierch, 0-157 days). The standard deviation for this parameter ranged from 13.7 days in the east (Białystok) to 22.7 days in Wrocław and 23.2 in Szczecin in the west. A considerable standard deviation was also found on the Baltic coast (Świnoujście, 22.4 days) and in the mountains (e.g., Kasprowy Wierch, 25.7 days).

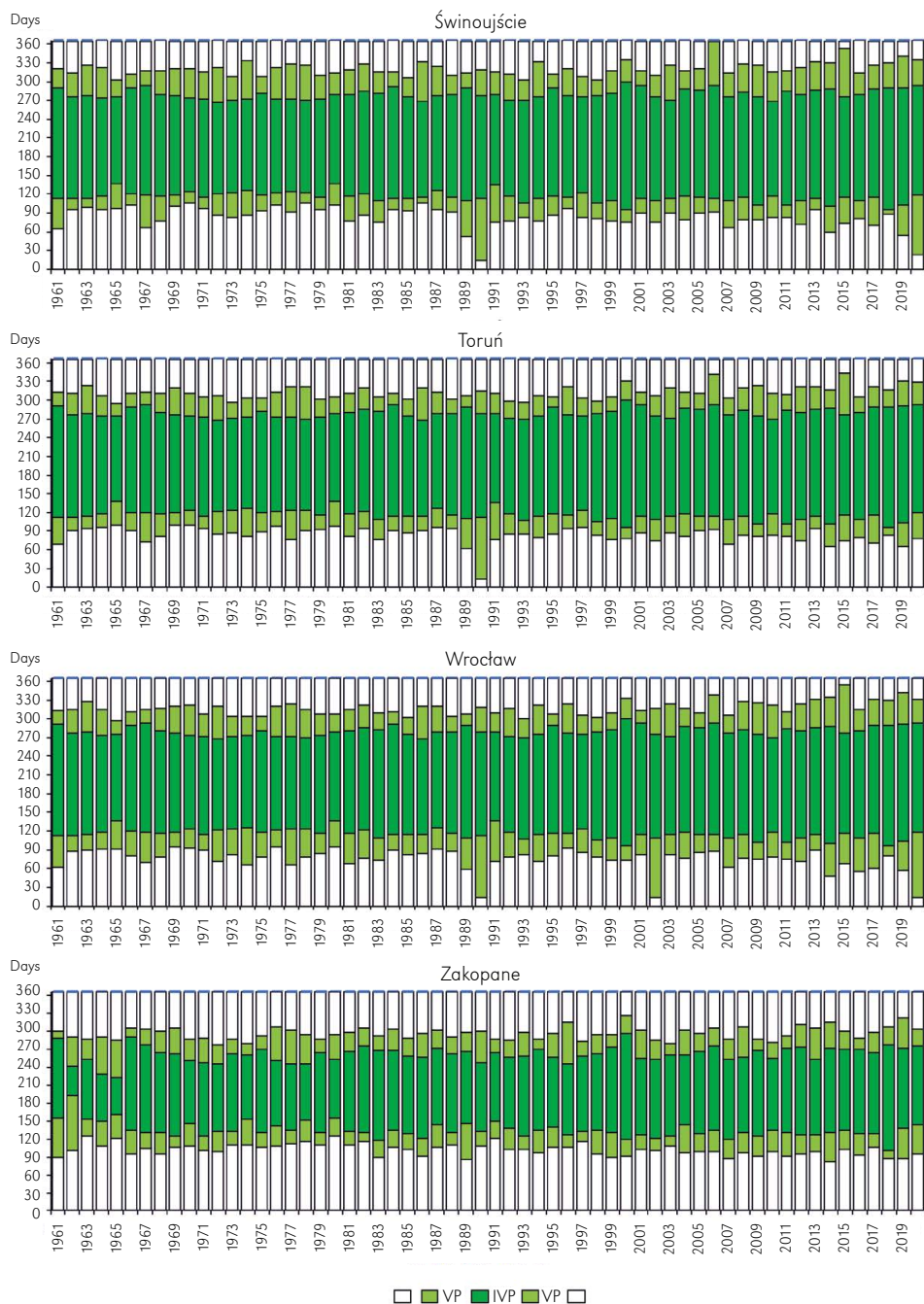


Figure 3. Vegetation period (VP) and intensive vegetation period (IVP) at selected stations in Poland in 1961-2020

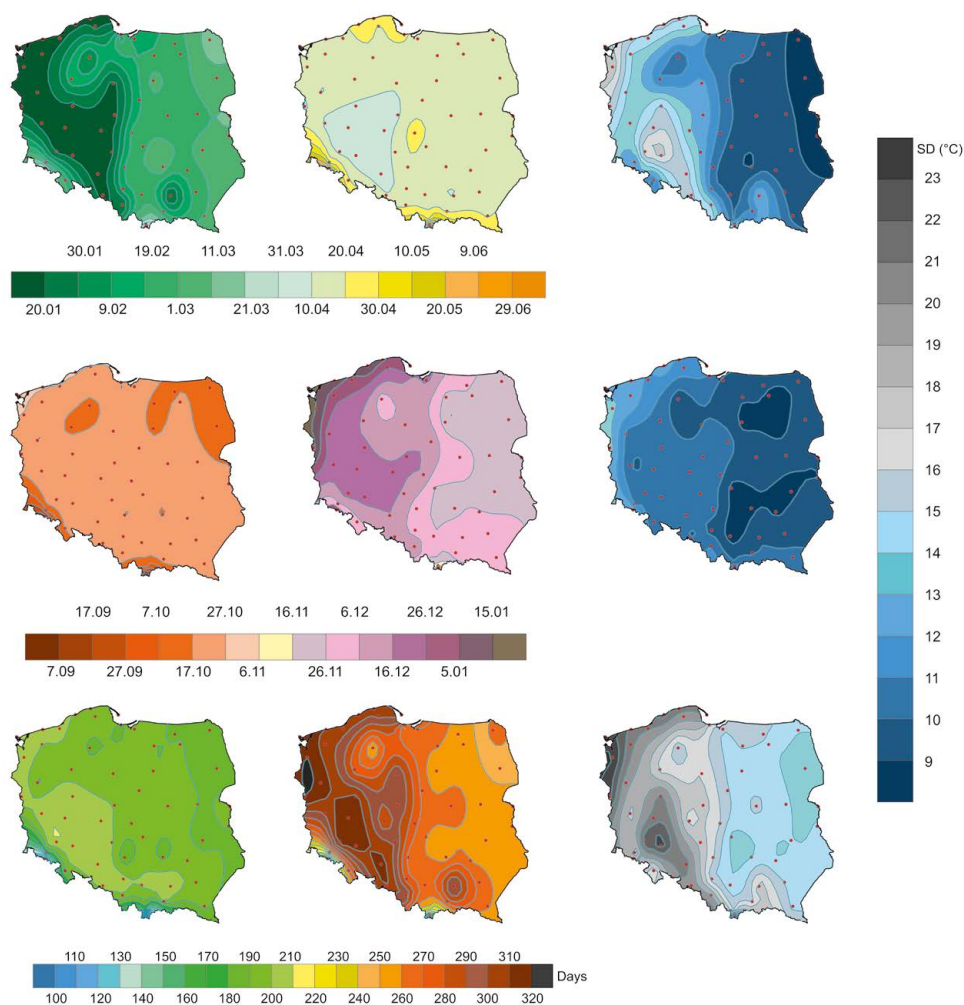


Figure 4. Variability of the occurrence of vegetation period in Poland in 1961-2020: Top panel: beginning of the vegetation period in Poland (earliest, latest, and standard deviation). Middle panel: end of the vegetation period in Poland (earliest, latest, and standard deviation). Bottom panel: duration of the vegetation period (shortest, longest, and standard deviation).

Trends in the onset and duration of the vegetation period

Comparing the dates of onset and termination of the VP in the years 1961-1990 and 1991-2020, it was found that the onset of VP was greatly accelerated: e.g. by 11 days in Świnoujście (3 April-24 March) or by just 4 days in Gdańsk (Tab. 1). In the lowland part of the country, the advancement reached approximately 7-8 days: e.g. in Warsaw

(31 March-24 March), and in the mountains it ranged from 9 days (Zakopane) to 13 days on Kasprowy Wierch (12 June-31 May). The end of the VP became slightly delayed, by 2-5 days: e.g. in Wrocław (8 November-13 November). With the opposite trends in the onset and termination, the duration of the VP was extended by up to 12 days in Wrocław and by 17 days in the mountains (Kasprowy Wierch).

An analysis of the trends in the VP's onset confirmed these changes. At 89% of the stations a statistically significant trend ($p < 0.05$) was found, indicating advancement in the date the VP beginning (Fig. 5). The most remarkable changes in the date the VP beginning occurred on the Baltic coast (-4.1 days/10 years in Świnoujście) and in the west of the country (-3.7 days/10 years in Wrocław). This means an advancement of 22-25 days in the analysed period. A smaller advancement of approximately -2 days/10 years took place in the east, south and centre of Poland. On the other hand, the end of the VP turned out to be significantly delayed at 38 stations (69.1%). The greatest changes occurred in the west of Poland (Wrocław, 2.95 days/10 years; Opole 2.82; Resko 2.76). In the east of the country, the changes either were not statistically significant or did not exceed 2 days.

Quite substantial changes occurred in the duration of the VP. At as many as 94.5% of the weather stations, statistically significant vegetation trends were observed (Fig. 5). In western Poland, the changes reached 6.7 days/10 years in Wrocław and a similar value of 6.5 days/10 years in Świnoujście on the Baltic coast. This means that the duration extended by ~40 days. In eastern Poland, the changes reached 2-3 days: e.g., 2.86 days/10 years in Lublin.

Intensive vegetation period
Spatial distribution of the onsets and duration of the intensive vegetation period

The period of intensive vegetation begins the earliest in the south of Poland (excluding the mountains) (Tab. 1, Fig. 6). As early as 21 April in Tarnów and 22 April in Opole and Racibórz, the mean diurnal air temperature exceeded



Figure 5. Trends (days/10 years) related to the beginning (A), end (B) and duration (C) of the vegetation period in Poland in 1961-2020. Stations with a statistically significant trend are marked on the maps

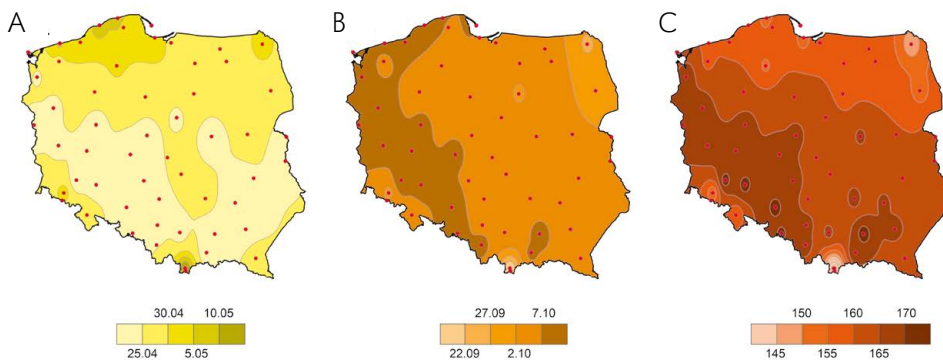


Figure 6. Fig. 6. Onset (A), termination (B) and duration in days (C) of the intensive vegetation period in Poland in 1961-2020

10°C. On subsequent days, the onset of IVP reached further and further to the north. On the Baltic coast, the IVP began only on 10 May (Ustka, Łeba, Hel). In the northeast, it started with a delay (on 3 May in Suwałki), too. In the highest parts of the mountains, the IVP did not occur according to the mean values for 1961-2020. The end of the IVP progressed from east (Suwałki, 27 September) to west (Wrocław, 11 October; Świnoujście, 13 October). The longest IVP occurred in the south-east (Wrocław, Opole and Legnica, 172 days) and the south of Poland (Tarnów, 170 days). The shortest IVP was observed in the north-east of the country (Suwałki, 147 days) and on the Baltic coast (Gdańsk, 152 days). Generally, the IVP becomes shorter with the altitude in the mountains and occurs only occasionally at the highest-situated weather stations (Śnieżka and Kasprowy Wierch).

Variability of the onset and duration of the intensive vegetation period

A considerable year-on-year variability also characterises the intensive vegetation period (IVP). At individual stations the onset of IVP can vary up to 92 days (Zakopane, 10 April – 11 July). Apart from the mountains, big differences occur in Łębork in the Pomeranian Lake District (15 March – 22 May, i.e. up to 68 days). More balanced conditions occur on the Baltic coast (Hel, 21 April to 26 May, i.e. 35 days). The standard deviation for the onset dates ranged from 7.3 days in Białystok to 16.1 days on Śnieżka in the Sudetes.

The end dates of IVP varied up to 29 days in Hel (30 September – 28 October), but even greater differences were observed in Zakopane (10 August – 22 October, i.e. 73 days).

At the analysed stations, there were considerable differences in the duration of IVP as well. In the lowlands, the duration reached from 49 days (Hel) to 69 days (Łębork). The standard deviation was the greatest in Zakopane (21.3 days), then in Łębork (15.7) and Suwałki (11.2).

Trends in the onset and duration of the intensive vegetation period

Comparing the periods 1961-1990 with 1991-2020 made it possible to determine the size of changes in the IVP (Tab. 1). In the latter decades, 1991-2020, the onset of the intensive vegetation period took place 4-9 days earlier compared with 1961-1990, and, for example, in Wrocław it began on 17 April, instead of 26 April. At the same time, the IVP terminated 2-5 days later (e.g., moving from 8 to 13 October in Wrocław). Therefore, the duration of IVP extended by up to 14 days (e.g. Wrocław, from 165 to 179). By comparison, the average start date of the period in Warsaw changed from 20 to 23 April, its end moved from 5 to 8 October, and the IVP was 10 days longer (from 171 to 161 days).

These changes were confirmed by analysing the trends. At as many as 90.9% of the stations, a statistically significant earlier occurrence of the onset of IVP was observed (Fig. 7). The most significant changes



Figure 7. Trends (days/10 years) related to the beginning (A), end (B) and duration (C) of the intensive vegetation period in Poland in 1961-2020. Stations with a statistically significant trend are marked on the maps

happened in the west of Poland (Gorzów Wielkopolski, -2.92 days/10 years) and on the Baltic coast (Kołobrzeg, -3.12 days/10 years). An even greater advancement took place in Zakopane (-3.57 days/10 years). At mountain stations, IVP hardly occurred, but in the decade of 2011-2020, there were 9 years with IVP on Śnieżka, and 6 such years on Kasprowy Wierch. In eastern Poland, the trends regarding the IVP start dates were of little (< -2 days) or no statistical significance.

Lesser changes marked the end of the intensive vegetation period. In lowland Poland, the trend ranged from 1 to 2 days/10 years (Wrocław, 1.91 days/10 years). A greater delay was observed in the mountains, with 2.19 days/10 years in Zakopane and 4.49 days/10 years on Śnieżka, though at the latter station, the IVP hardly ever occurred in many decades.

At almost all stations (96.4%), the IVP was found to be extended (Fig. 7). The greatest changes occurred in the west of the country (Wrocław, 4.48 days/10 years) and the Baltic coast (Kołobrzeg, 4.45 days/10 years). In the east, the values did not exceed 3 days/10 years (Białystok, 2.15 days/10 years). At the mountain stations, in 1961-2020 the IVP extended by 39 days on Śnieżka (trend: 6.57 days/10 years) and by 35 days in Zakopane (5.76 days/10 years).

Discussion

According to the Sixth Assessment Report IPCC (2021) there is an increase in global air temperature. In Poland, air temperature increased at a rate of 0.2-0.3°C/10 years (Ustrnul et al., 2021; Kejna & Rudzki, 2021). One of the indications of global warming is the change in the duration and start- and end-dates of thermal seasons) and the vegetation season (Czernecki & Miętus, 2017; Kejna & Pospieszyska, 2023).

In Poland, there is a significant variation in climate and weather conditions from west to east. The transitional nature of the climate is visible as a result of the decreasing frequency of maritime air masses towards the east, where a greater share of continental air

masses is noted (Woś, 2010; Kożuchowski, 2011). This causes a varied length of the vegetation period.

The onset of the VP occurred at the end of March and the beginning of April, and it progressed from the west to the east. It covered the whole area of Poland in 16 days., as proven by MODIS satellite data (Bartoszek et al., 2015) The VP started particularly late on the coast of the Baltic Sea (Tylkowski 2015). The termination of the VP ended earliest in the east at the end of October or the beginning of November and the latest on the coast. In the Carpathians and the Sudetes mountains, the VP gets shorter with altitude (Bochenek et al., 2013; Bochenek, 2016). The obtained dates confirmed the results of earlier studies, but there was even greater advancement of the onset, a delay of the termination, and a general extension of the VP (Bartnicki, 1948; Molga, 1980; Olszewski & Żmudzka, 2000; Tomczyk & Bednorz, 2022).

In Poland, there is a significant variability of VP occurrences from year to year. It is a typical feature of other Central European countries, as well (Szyga-Pluta & Tomczyk, 2019). In recent decades, these changes have significantly accelerated, especially in the west of Poland. The onset of VP has been particularly accelerated in autumn, when the vegetation period ends, the changes are smaller. The obtained results support the trends found in earlier publications (Olszewski & Żmudzka, 2000; Żmudzka & Dobrowolska, 2001; Górski, 2006; Węgrzyn, 2008; Mager & Kopeć, 2010; Żarski et al., 2012; Nieróbca et al., 2013; Kruzel et al., 2015; Tomczyk & Szyga-Pluta, 2016; Chojnacka-Oźga & Oźga, 2018 and 2023; Koźmiński et al., 2021; Szyga-Pluta et al., 2023).

Corresponding patterns have been observed in other areas of the world. The changes are global but they are especially evident at temperate latitudes (Barichivich et al., 2013; Wu et al., 2021). Changes in the onsets of the VP also vary by region (Carter, 1998; Menzel et al., 2003; Dong et al., 2013; Cui et al., 2017). In Europe, the duration of VP extended (Menzel & Fabian, 1999; Walther

& Linderholm, 2006; Linderholm et al., 2008; Tomczyk & Szyga-Pluta, 2016, 2018, 2019; Tomczyk et al. 2019; Szyga-Pluta et al., 2019, 2023). In Czechia, the VP extended on average by 24 days in 35 years (Kolářová et al., 2014). In Slovakia most significant changes occurred especially in the south of the country (Cimo et al., 2022; Kiss et al., 2022). Similarly, in 1950-2019 in the Balkans, the change reached two weeks (Chervenkov & Slavov, 2021). The onsets of VP in Europe tend to exhibit a strong inter-annual and decadal variability with a tendency for long vegetation periods to increase in frequency (Linderholm et al., 2008). This was confirmed in the studies of Tomczyk & Szyga-Pluta (2017) and Szyga-Pluta & Tomczyk (2019).

It is essential to identify the mechanisms leading to changes in the duration of the vegetation period. Analyses have demonstrated that the duration of the VP is primarily dependent on the date of its onset, whereas a delay in its termination is less important (Czernecki & Mietus, 2017; Kejna & Pospieszyńska, 2023). In Europe, a 1°C increase in air temperature extends the VP by 2.5 days if it occurs in the first part of the VP but only by 1 day in autumn (Menzel et al., 2003). On the other hand, Karlsen et al. (2007) stated that a 1°C increase in temperature in spring indicates an earlier start of the VP by 5-6 days. There are also more significant changes in the oceanic climate than in the continental one. A similar relationship has been found in Poland (Bochenek et al., 2013; Chojnacka-Ożga & Ożga, 2023).

Large-scale fluctuations in the atmospheric circulation regime may be a reason for these changes (Menzel et al., 2003). In Europe, changes in the atmospheric circulation described by means of North Atlantic Oscillation (NAO) and Arctic Oscillation (AO) are significant (Wu et al., 2021). The NAO index strongly affects the phenophases of plants in Europe (Linderholm, 2006; Craig & Allan, 2021). In Poland Marsz & Żmudzka (1999) and Bartoszek & Węgrzyn (2011) found that changes in the duration of the VP depend on the NAO. An earlier onset of VP depends

on the influx of air masses from the west, i.e. the Atlantic Ocean, and the advection of continental air masses postpones vegetation (Bartoszek et al., 2015). On the other hand, research by Tomczyk et al. (2019) indicated that phases of the Arctic Oscillation have most significant impact on the onset of the VP, and the influence of the NAO is weaker. However, the end of the VP is affected by the East Atlantic Oscillation. EA phase driving an earlier vegetation season onset (Craig & Allan 2021).

Similar changes apply to the IVP, which in Poland begins earliest in the south (excluding the mountains) – in the last 10 days of April – and reaches the Baltic coast by 10 May. The end of the IVP happened on average at the end of September or the beginning of October, moving from the northeast to the west of the country. There are considerable differences in the duration of the IVP: from 147 days (NE Poland) to 172 days (S). The IVP gets shorter with altitude in the mountain. At the highest peaks of the Tatras and the Sudetes, it occurs only occasionally.

Tomczyk & Bednorz, 2022; Żarski et al., 2012 and Chojnacka-Ożga & Ożga, 2023 reached similar conclusions. It was found that the onset of IVP occurred earlier by 4-9 days, comparing the years 1961-90 and 1991-2020. Termination of IVP was delayed by 2-5 days (trend -3.12 days/10 years). Smaller changes occurred in the end dates of the IVP (1.9 days/10 years) in the southwest of Poland. IVP increases at a rate from 2.3 days in the east to 4.5 days/10 years in the west of the country. Even more significant changes occurred in the mountains. The results are close to those obtained by Nieróbca et al. (2013) and Tomczyk & Szyga-Pluta (2018).

Agroclimatic scenarios based on global models indicate that this overall trend will continue (Qian & Gameda, 2010; Christiansen et al., 2011). Xia et al. (2015) argue that the onset of the IVP period will occur sooner in the northern hemisphere. In Northern Europe, according to the RCP scenarios, the summer period (with temperatures > 10°C) will be 30 days longer in 2040-2069 as com-

pared with 1971-2000 (Ruosteenoja et al., 2020). In 2021-2050, in the south of Norway, according to Skaugen & Tveito (2004), the VP will be as long as in southern Britain, the Netherlands or northern Germany. In Slovakia, the VP will have extended by 55 to 140 days by 2050 (Kiss et al., 2022). In Poland, depending on the assumed climate scenario, in 2030, the VP will be 10-17 days longer than in 1971-2000, and 22-30 days longer by 2050 (Nieróbca et al., 2013). According to the greenhouse gas concentration model RCP 8.5, by the end of the 21st century, the VP will have extended by even 60 days in Poland (Graczyk & Kundzewicz, 2016). On the other hand, the research of Szyga-Pluta et al. (2023) suggests that the onset of the VP will happen 5 to 10 days earlier in 2040-59 than in 1985-2004.

The changes in the onsets of VP will have various environmental and economic consequences, especially in agriculture (Trnka et al., 2011; Cimo et al., 2022). There will be changes in the range of occurrence of various plant species, which are increasing their incidence in the northern hemisphere at a rate of 6.1 km per decade (Parmesan & Yohe, 2003).

The more thermophilic tree species will increase their incidence at the expense of species that prefer harsher climates (Sparks & Menzel 2002; Ryan & Archer, 2008). Menzel & Fabian (1999). In recent decades in Poland, not only have the dates and duration of the VP been changing, but so too have the thermal resources of that period. In 1966-2015 the mean air temperature substantially increased during the VP (Tomczyk & Szyga-Pluta, 2019). An analysis of the Growing Degree Days indicated their substantial growth (Żmudzka, 2012; Radzka, 2021). At the same time, precipitation during the VP has not been observed to go up (Tomczyk & Szyga-Pluta, 2019); hence, the ongoing increase in evapotranspiration (ET_o) (Araźny et al., 2023), is causing droughts to occur more frequently (Kalbarczyk & Kalbarczyk, 2022) and is leading to negative consequences for the economy, especially agriculture. The conditions of forest cultivation are also changing (Chojnacka-Ożga & Ożga, 2023).

Agriculture has also changed; phenophases have shifted in spring barley cultivation, e.g. in Czechia (Moravia) (Středová et al., 2017). In Poland, the harvesting time will start earlier at 23 days for this crop, and by even 30 days for wheat (Marcinkowski & Piniewski, 2018). Thermophilic plants can be grown now (Skowera & Kopeć, 2008; Żarski et al., 2012; Żmudzka, 2012); the conditions for vine cultivation in south-eastern Poland are increasingly better, and early varieties can be grown (Kopeć, 2009). Nevertheless, such an earlier onset of VP poses certain threats to the development of plants, especially at the early stages of vegetation. In Poland, the number of ground frost days during the VP in 1971-2000 did not show any statistically significant changes (Kozłowski et al., 2021). Although the period of time without ground frost has become longer in Poland, there is still a real risk that late ground frost will occur (Bielec-Bąkowska & Piotrowicz, 2011). As a result, plants are still at risk of destruction by frost (Nidzgorska-Lencewicz et al., 2024). This applies to all regions in the moderate climate zone where the vegetation period is undergoing extension (Liu et al., 2016).

The ongoing changes in the VP and IVP are a prominent sign of climate warming. They will lead to numerous environmental threats. Adaptation measures need to be introduced in various areas of life and human economy.

Summary

Based on analysis of 1961-2020 data from 55 weather stations, it was found that there is significant spatial variation in Poland's onset, end dates, and duration of VP and IVP. The onset of the VP and IVP occurred earliest in western Poland, the latest in the east of the country, and on the Baltic Sea shore. The difference is 16 days for VP and 19 for IVP. In the mountains, the onset of VP and IVP is delayed with altitude, and in the highest parts of the mountains, IVP does not occur. The end of VP and IVP progresses from east to west of Poland. These periods end later on the Baltic Sea. In the mountains, the end

of VP and IVP occurs earliest at high altitudes above sea level, vegetation lasts longer in the valleys. The length of VP and IVP shortens from west to east of Poland, e.g. VP from 237 to 204 days, and IVP changes from 172 to 147 days. In the mountains, these periods are shorter with altitudes above sea level. The VP and IVP periods show significant variability from year to year, especially in western Poland. More stable conditions occur in the eastern part of the country. VP and IVP start earlier and earlier, which is confirmed by comparing the years 1961-90 and 1991-2020. The difference for VP is 11 days in western Poland, and 7-8 days in the east. These periods end later and later, e.g. VP by 5 to 2 days. IVP starts 9-4 days earlier and ends 5 to 2 days later, respectively. There was a straightforward extension of VP by 16 days in western Poland and 10 days in eastern Poland. In western Poland, IVP was extended by 14 days. Trend analyses confirm this. With the general tendency for VP and

IVP to lengthen, thermal contrast between western and eastern Poland is increasing. Changes in the appearance of VP and IVP affect the functioning of the natural environment and human activities.

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Unless otherwise stated, the sources of tables and figures are the authors', on the basis of their own research.

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