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Research into Meteorological Drought in Poland during the Growing Season from 1951 to 2020 Using the Standardized Precipitation Index

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Abstract: Meteorological drought (*MDr*) causes considerable economic losses in many countries, including in relation to agriculture. To examine the diversity of seasonal meteorological drought in Poland, the study uses monthly precipitation sums in the period from March to November, collected from 74 ground-based meteorological stations in 1951–2020. The paper defines meteorological drought on the basis of the standardized precipitation index in three seasons (*SPI-3*) and differentiates three degrees of drought intensity: extreme, severe and moderate. The study also calculates the size of Poland's area affected by meteorological drought (*AAMDr*) and determines the relationship between *AAMDr* and *SPI-3*. *MDr* in Poland occurred more frequently in spring and autumn (every 4–5 years) than in summer (every 7 years). In the areas affected by extreme drought, precipitation was below the average, mainly ≤50% of the climatic norm, and air temperature values were below or above the average of the climatic norm, mainly ranging from −1.0 to 1.0 °C. A significant negative correlation between *AAMDr* and *SPI-3* indices was found. The obtained results could be useful for managing climatic risk and developing regional and local agriculture adaptation plans aimed at mitigating the effects of climate change.

Keywords: agriculture; climate change; monitoring; precipitation deficit; spatial distribution

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1. Introduction

Meteorological drought (*MDr*) is the result of at least several climatic factors interacting with each other, including astronomical, geographical, circulational and anthropogenic [1–5]. In Poland, *MDr* occurs as a result of anticyclonic patterns of atmospheric circulation over Europe, which are blocked by low-pressure systems [6]. Cyclonic circulation types from the east and south-east are also conducive to the occurrence of drought, though to a much lesser extent [7]. In Poland, such weather conditions occur in March, May, June and October [8]. It was also found that there is a weak but significant link between ENSO and surface hydrology in SW Poland [9].

In the last decade, the frequency and intensity of meteorological droughts have increased in most parts of Europe, mainly in Southern and Western Europe, but also in the region of the Carpathians [10,11]. Northern Europe is an exception. Its conditions, as proved, are becoming more and more humid and thus the frequency and severity of drought have shown downward tendencies; Central and Eastern Europe have acted as a transition zone [10]. The research conducted on a world scale indicates upward trends for droughts in central and eastern parts of North America, Western Canada, South America, Europe, Central Asia, Russian Far East, South Asia, Southern Africa and Central West Australia [12]. The same research shows downward trends mainly for Southern Canada, the north of South America, Central and North Africa, parts of Europe (e.g., Germany and Turkey), the east of Australia and especially for eastern parts of China and Mongolia. On the other hand, McCabe and Wolock's [13] research for 1901–2009 does not confirm a drought trend on a global scale; at the same time, it was proved that drought intensified in the northern high latitudes. In the Sixth Assessment Report of the IPCC [14], it was stated that with global warming of 2 °C and higher, several regions in Africa, South America and Europe would experience an increase in the frequency and/or intensity of agricultural and ecological droughts; growths are also forecast for Australasia, Central and North America and in the Caribbean. In Poland, which is included in the region of Central and Eastern Europe, it is predicted that meteorological drought will occur more frequently, particularly in spring [10,15].

Local, short-term meteorological drought usually causes temporary inconveniences that may be almost undetectable in ecosystems. Long-term *MDr* that affects entire regions of a given country has a greater impact on society and the economy [16]. The phenomenon of drought causes considerable damage and economic losses in the EU, which are estimated at more than 100 billion euros in the last 30 years [17,18]. These studies showed that between 1993−2013 as much as 80% of lower wheat yields in 25 member states of the EU, including Poland, were caused by drought and heat waves. In the EU, the mitigation policy of socioeconomic and meteorological drought effects was shaped by such documents as: the Water Framework Directive (WFD) 2000/60/EC, A Blueprint to Safeguard Europe's Water Resources [19]. In the world, the effects of droughts in agriculture are mitigated through irrigation systems, provision of water resources by building dams, improvement of water retention capacity and also development of comprehensive interbasin water transfer. Short- and long-term drought mitigation methods in different regions of the world are a subject of research and practical guidelines [19,20].

MDr occurs unevenly throughout Poland: its intensity varies, and it is seasonal. Therefore, its impact should be considered in relation to the place and time of its occurrence, among other things [21–23]. In Poland, *MDr* may result in heavy agricultural losses, which are reflected in reduced harvests and poor-quality agricultural produce [24–29]. Negative effects of *MDr* increase in specific conditions of Poland's geographical environment (uneven distribution of natural bodies of water: mostly in the north and a latitudinal arrangement of the main mountain ranges located in the south) and also as a result of wrong water management policies in the previous century (focused on land drainage for the purposes of agriculture and settlement of that time). In order to reduce water deficits, temporary limitations on the use of water for non-potable purposes are often introduced.

For this reason, monitoring of meteorological conditions is very important, particularly in such countries as Poland, in which agriculture is a significant sector of the economy, and where agricultural land accounts for approx. 60% of Poland's area and forest land for another 30%. The monitoring of *MDr* uses data from ground-based stations, which are evenly distributed in particular regions of a country, as well as from satellite images [10,15,22,30]. In Poland, agricultural drought monitoring is conducted by the Institute of Soil Science and Plant Cultivation–State Research Institute in Puławy. During the growing season of plants, i.e., from 21 March to 30 September, it prepares 10-day reports about the values of the climatic water balance (CWB) for particular communes (3058 communes), taking into consideration water requirements of main plant species and plant groups cultivated in Poland for four categories of soils of different drought susceptibility [31]. Plant species and groups covered by drought monitoring of the institute include: winter and spring cereals, maize, oilseed rape, potato, sugar beet, hops, tobacco, field vegetables, fruit trees and bushes, strawberries and legumes. The information about agricultural drought is announced by the minister competent for agriculture from 21 May to 20 October. The legal basis for organizing drought monitoring is the provisions of the Act on the Crop and Livestock Insurance [32].

Meteorological drought can be determined based on meteorological indices, which help to evaluate its variations in time and space, its intensity and also sometimes its beginning and end [33–36]. One of the best (and simplest) indices that is used to identify

MDr and to evaluate its intensity is the standardized precipitation index (*SPI*) [37,38]. SPI can be calculated in various time scales, e.g., *SPI-1*–a month, *SPI-3*–a season, *SPI-6*–half a year, *SPI-12*–one year and *SPI-24*–two years [39–43]. In 2010, the World Meteorological Organization recommended the *SPI* index for the monitoring of meteorological drought by national meteorological services [44]. Currently, *SPI* is used for drought monitoring by, for example, the USA National Drought Mitigation Center [41] and the European Drought Observatory [45].

The aim of this work is to find the temporal and spatial diversity of the value of the standardized precipitation index (*SPI-3*) during three Polish seasons corresponding to the growing season from 1951 to 2020: spring (March to May), summer (June to August) and autumn (September to November). The study also aims to determine how much of Poland experienced meteorological drought (*AAMDr*) in the analyzed multi-annual period. The paper also examines the relationship between the *AAMDr* and *SPI-3* indicators.

2. Materials and Methods

The meteorological data are from ground-based monitoring of weather conditions operated by the Polish Institute of Meteorology and Water Management (IMGW-PB) (Figure 1).

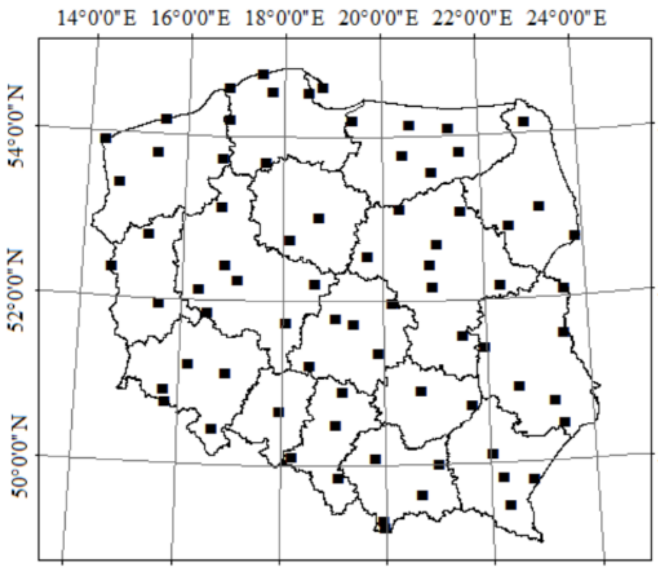

Figure 1. Location of the meteorological stations in Poland that were used in the study.

The paper uses precipitation sums (*Pr*, mm) and average air temperature (*Ta*, °C) in three seasons: spring (from March to May), summer (from June to August) and autumn (from September to November). The *Pr* and *Ta* data were collected from 74 meteorological stations from 1951 to 2020. In rare cases of incomplete meteorological data (approx. 2% of the dataset), these were supplemented from IMGW-PIB stations that were located closest to and best reflected the geographical conditions of the area with incomplete data. To this end, this paper uses linear and non-linear regression equations that describe the relationships between the analyzed series of data in the researched seasons. The goodness of fit between the regression functions and the empirical data was assessed on the basis of the coefficient of determination (R^2, %) and the Student's *t*-test. The homogeneity of seasonal *Pr* and *Ta* series was verified with Bartlett's test at a significance level of $\alpha < 0.05$ [46,47]. Average meteorological data values for Poland were calculated based on data from 74 IMGW-PIB stations. The reference period (climatic norm) was the multi-annual average from 1991 to 2020.

Meteorological drought in spring, summer and autumn was determined by means of the standardized precipitation index (*SPI-3*), calculated based on the following equation:

$$SPI\text{-}3 = \frac{f(Pr) - \mu}{\sigma} \quad (1)$$

where:

Pr–seasonal sum of precipitation;
μ–average value of the normalized series of precipitation sums;
σ–mean standard deviation of the normalized series of precipitation sums.

Prior to determining *SPI-3*, the series of seasonal precipitation sums was normalized with the use of a transformation function $f(Pr) = \sqrt[3]{Pr}$ [32].

SPI-3 reflects short- and medium-term humidity in an environment. This indicator enables seasonal estimation and classification of precipitation variation, and it is frequently applied for the purposes of agriculture [44]. Meteorological drought classes are adopted from the classification proposed by [36,37], presented in Table 1.

Table 1. Classes of meteorological drought according to the *SPI-3* index.

Class	Symbol	*SPI-3*
Extreme drought	Ed	≤ -2.0
Severe drought	Vd	$[-1.5; -2.0)$
Moderate drought	Md	$[-1.0; -1.5)$

The area of Poland affected by meteorological drought (*AAMDr*, %) was determined separately for each of the three seasons (spring, summer and autumn) according to the three *SPI* classes (Table 1) for each year from 1951 to 2020, i.e., for 210 seasons. *AAMDr* indicator calculations were performed in ArcGis 10.8.1. *AAMDr* was characterized using the following statistics: mean ($\overline{x}$, %), standard deviation (sd, %), and extreme value (max, %). The highest value was adopted as the extreme value for the selected seasons and particular classes of meteorological drought in the analyzed multi-annual period of 1951−2020. The linear trend (r) at significance levels of $\alpha < 0.1$ and $\alpha < 0.05$ was determined with the use of the Pearson correlation coefficient.

Evaluation of the dependence of *AAMDr* on *SPI-3* for Poland as a whole was performed by means of linear regression equations. For each of the examined seasons, six models were built for various ranges of the *SPI-3* index. These *ranges* were determined in the range between the lowest and the highest value of the *SPI-3* index in a given data series. The equations were verified by the coefficient of determination (R^2, %), the Student's *t*-test, Snedecor's *F*-distribution and the mean absolute error (*MAE*, %), which was determined with the formula:

$$MAE = \frac{1}{\mathrm{N}} \sum_{\mathrm{i}=1}^{\mathrm{N}} [\mathrm{yt} - \mathrm{Yt}] \quad (2)$$

where:

yt–actual value;
Yt–forecast value.

Using the inverse distance weighting method and ArcGis 10.8.1 software, maps were created that show the spatial distribution of *SPI-3*, *Pr* expressed as a percentage of the climatic norm (ΔPr, %), Ta expressed as a deviation from the climatic norm (ΔTa, °C), and the frequency of meteorological drought. This method was also used by [30]. The spatial resolution of the maps of the administrative division of Poland (NUTS 2) was 4 × 4 km. Statistical analyses were performed using STATISTICA 13.3. software and Excel 2010.

3. Results

3.1. SPI-3 Index–Spatial and Temporal Distribution

Out of the three analyzed seasons, extreme drought (*SPI-3* ≤ -2.0) occurred most frequently for the whole country in autumn in five years (1951, 1959, 1982, 2005 and 2011); this is followed by spring in three years (1953, 1959 and 1974); and least often in summer, when it occurred in two years (1992 and 2015) (Figure 2).

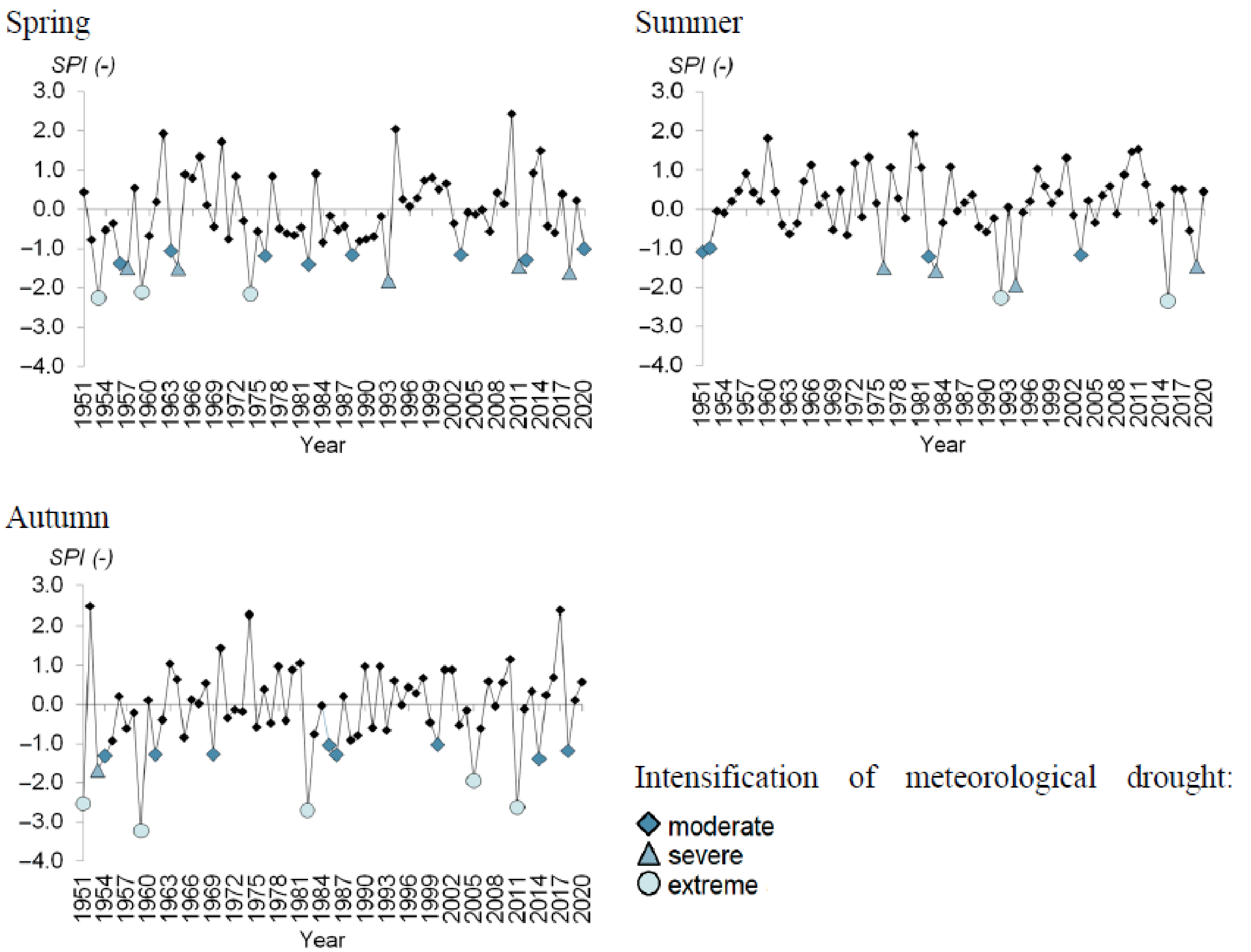

Figure 2. Variations in *SPI-3* for whole of Poland in spring, summer and autumn. Years 1951–2020.

The lowest *SPI-3* values were calculated for spring in 1953 (*SPI-3* = −2.2), for summer in 2015 (*SPI-3* = −2.4) and for autumn in 1959 (*SPI-3* = −3.2). Severe drought in Poland, *SPI-3* ϵ [−1.5; −2.0), was recorded with the following frequency: in five years in spring (1957, 1964, 1993, 2011 and 2018), in four years in summer (1976, 1983, 1994 and 2019) and in one year in autumn (1953). Moderate drought, *SPI-3* ϵ [−1.0; −1.5), was recorded 8 times in transitional seasons in spring (1956, 1963, 1976, 1982, 1988, 2003, 2012 and 2020) and autumn (1954, 1961, 1969, 1985, 1986, 2000, 2014 and 2018), but only four times in summer (1951, 1952, 1982 and 2003). In transitional seasons, *MDr* occurred every 4–5 years for the whole country and every 7 years in summer.

Meteorological drought in Poland occurred in all the examined seasons in only one year: 1982. In this year, the drought was moderate in spring (*SPI* = −1.2) and summer (*SPI* = −1.5), and it was extreme in autumn (*SPI* = −2.7) (Figure 2). In seven of the 70 analyzed years, *MDr* of varying intensity was recorded in two seasons: in spring and summer in 1976 and 2003; in summer and autumn in 1951; and in spring and autumn in 1953, 1959, 2011 and 2018.

According to *SPI-3* calculated for the whole of Poland, extreme drought occurred in three spring seasons. However, its intensity and occurrence across particular regions of the country in these seasons was very diverse (Figure 3). In the spring of 1953, extreme drought was recorded in east Poland; in 1959, extreme drought was recorded in smaller areas located in the northwest, central and southeast parts of the country; in 1974, extreme drought was recorded mainly in the north of Poland. In the areas with *SPI-3* ≤ -2.0, the recorded precipitation sum was lower than the average, mainly $\leq 50\%$ of the climatic norm (ΔPr). At the same time, air temperature reached values below or above the average of the climatic norm (ΔTa) and generally fluctuated within the following ranges: from -2.0 to -0.5 °C in 1953, from -0.5 to 0.5 °C in 1959 and from -1.5 to -1.0 °C in 1974.

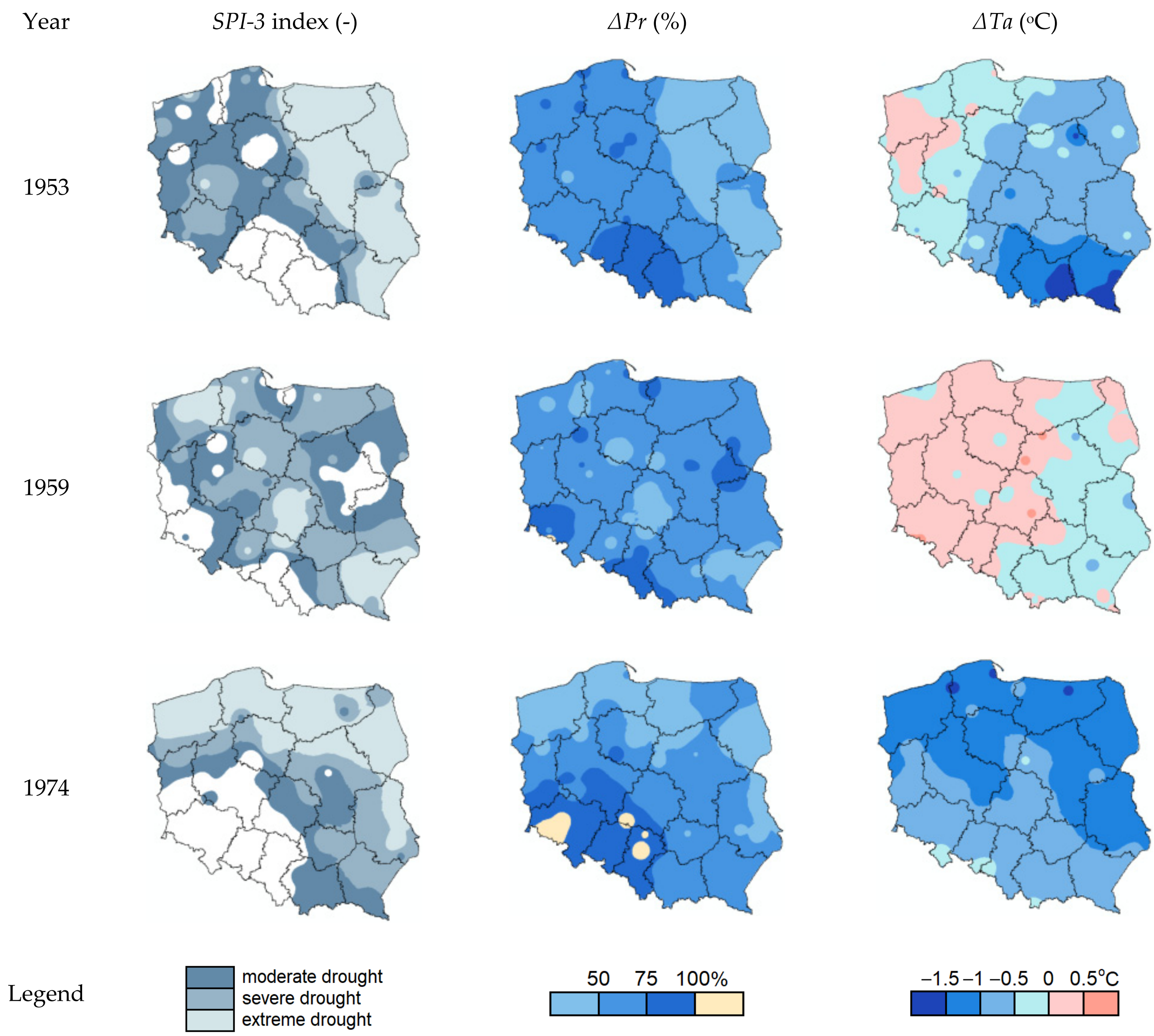

Figure 3. Spatial distribution of *SPI-3*, ΔPr and ΔTa in Poland in spring in years when the *SPI-3* value for a given area was ≤ -2 (1953, 1959 and 1974). Notes: ΔPr (%)–precipitation sum expressed as a percentage of the climatic norm, ΔTa (°C)–air temperature deviation from the climatic norm.

In summer, *MDr* of extreme intensity occurred in 1992 in northeast Poland and in 2015 in east and south Poland (Figure 4). Meteorological drought was recorded at $\Delta Pr \leq 50\%$ of the climatic norm and $\Delta Ta \geq$ of the climatic norm, fluctuating between 0.0 and 1.0 °C.

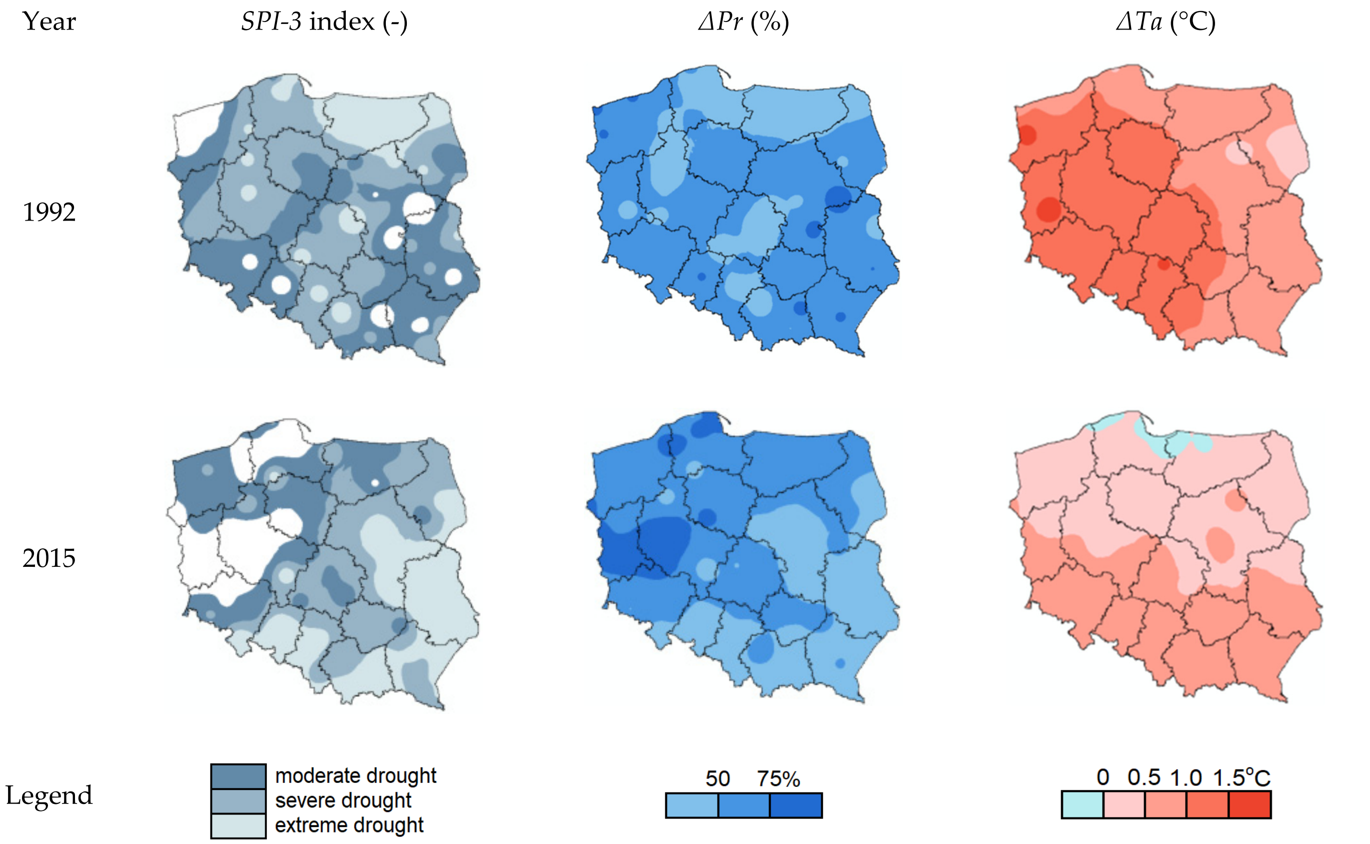

Figure 4. Spatial distribution of *SPI-3*, ΔPr and ΔTa in Poland in summer in years when the *SPI-3* value for a given area was ≤ -2 (1992, 2015). Notes as in Figure 3.

In autumn, like in the other two analyzed seasons, extreme meteorological drought occurred in different parts of Poland (Figure 5). In 1951, extreme drought was identified in north and central Poland; in 1959, *MDr* was identified in almost the whole of Poland, except for the northeast part; in 1982, it was recorded in west Poland. In 2005, extreme drought was recorded only in small areas in the central and southern parts of the country; in 2011, extreme drought was identified in east, central and southeast Poland. During extreme drought, ΔPr was most often within 0–50% of the climatic norm; however, ΔTa oscillated between <-2 °C in 1959 and >1.5 °C in 1982.

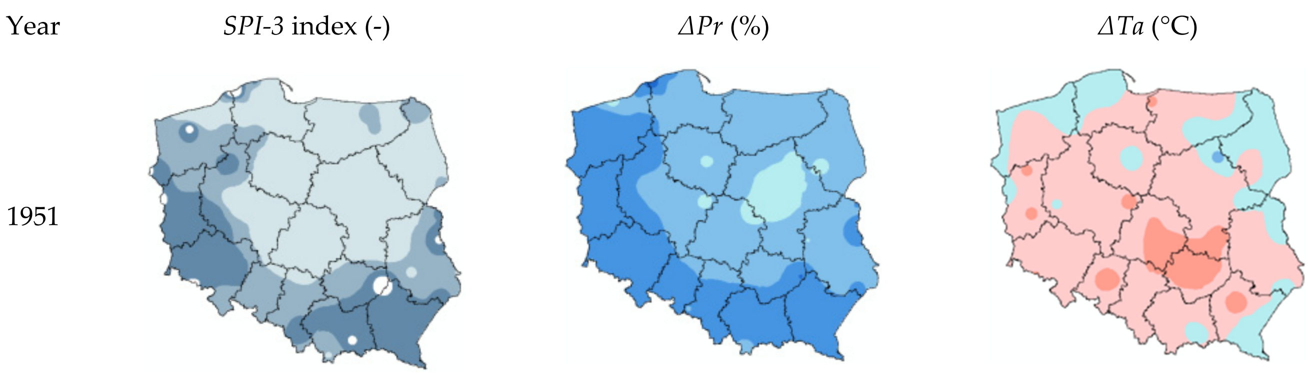

Figure 5. *Cont.*

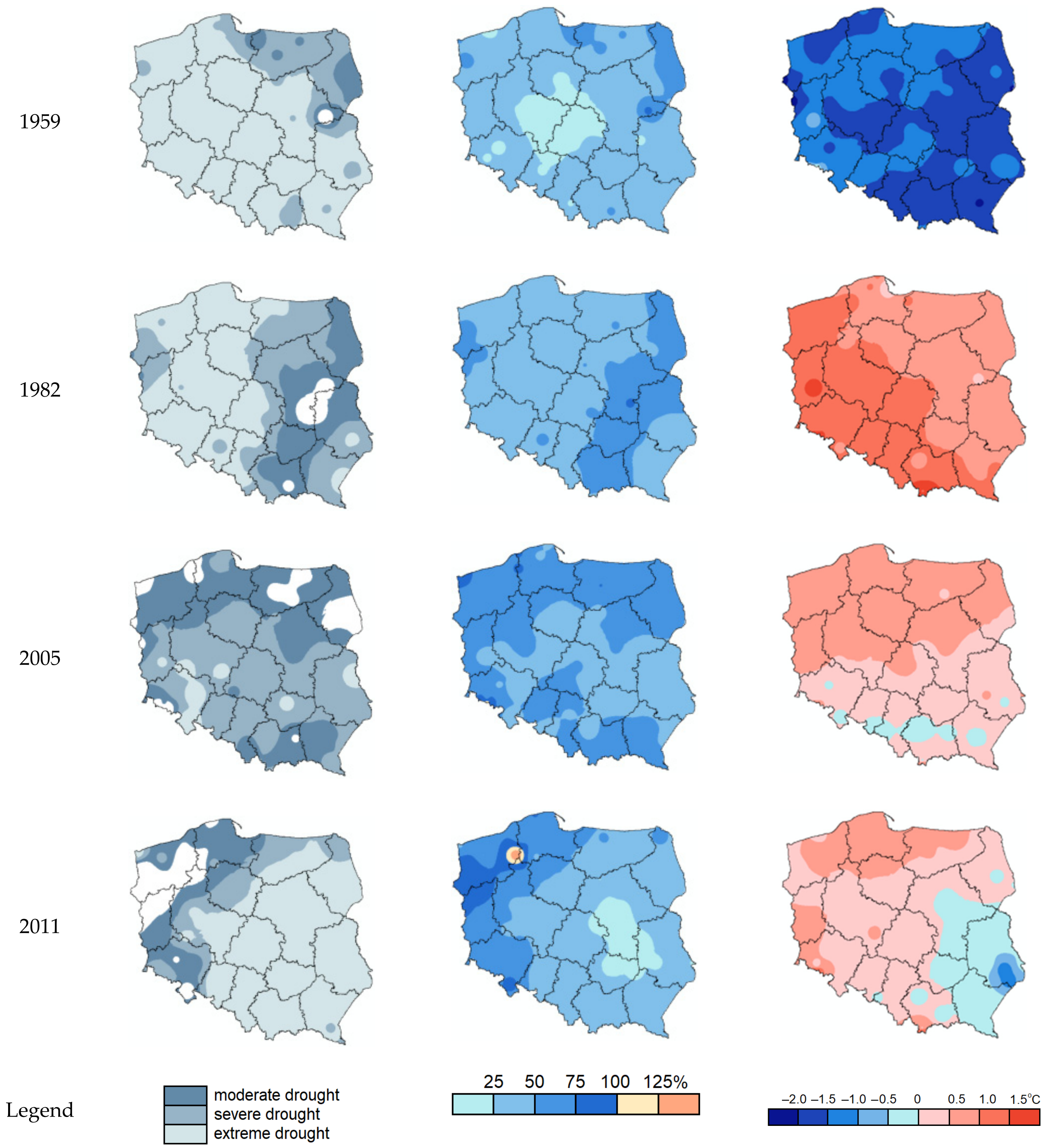

Figure 5. Spatial distribution of *SPI-3*, Δ*Pr* and Δ*Ta* in Poland in autumn in the years when the *SPI-3* value for a given area was ≤−2 (1951, 1959, 1982, 2005 and 2011). Notes as in Figure 3.

The monitoring of *MDr* and consequently the assessment of its impact on agriculture takes into account not only the intensity but also the frequency of this phenomenon. The frequency of meteorological drought is not uniform across Poland and depends on the season (Figure 6). In spring, *MDr* identified on the basis of *SPI-3* occurred most frequently in north (from 30% to 35%) and east Poland (from 25% to 30%); in summer, drought was identified mainly in north and central-west Poland (from 15% to 20%); in autumn, drought occurred primarily in northwest and south Poland (from 20% to 30%).

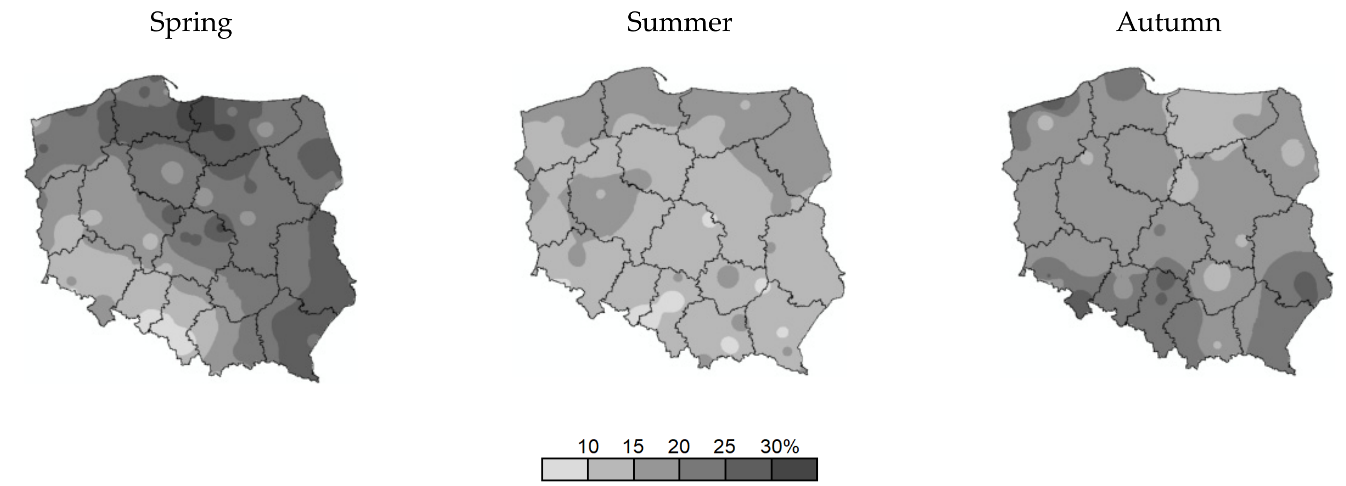

Figure 6. Frequency of three types of meteorological drought (moderate, severe and extreme), determined on the basis of the *SPI-3* index in spring, summer and autumn. Years 1951–2020.

In the spring season, *SPI-3* displays a significant (at a level of $\alpha < 0.1$) negative trend in 1951–2020, which means that year-by-year *MDr* will intensify, mainly in southwest Poland (Figure 7).

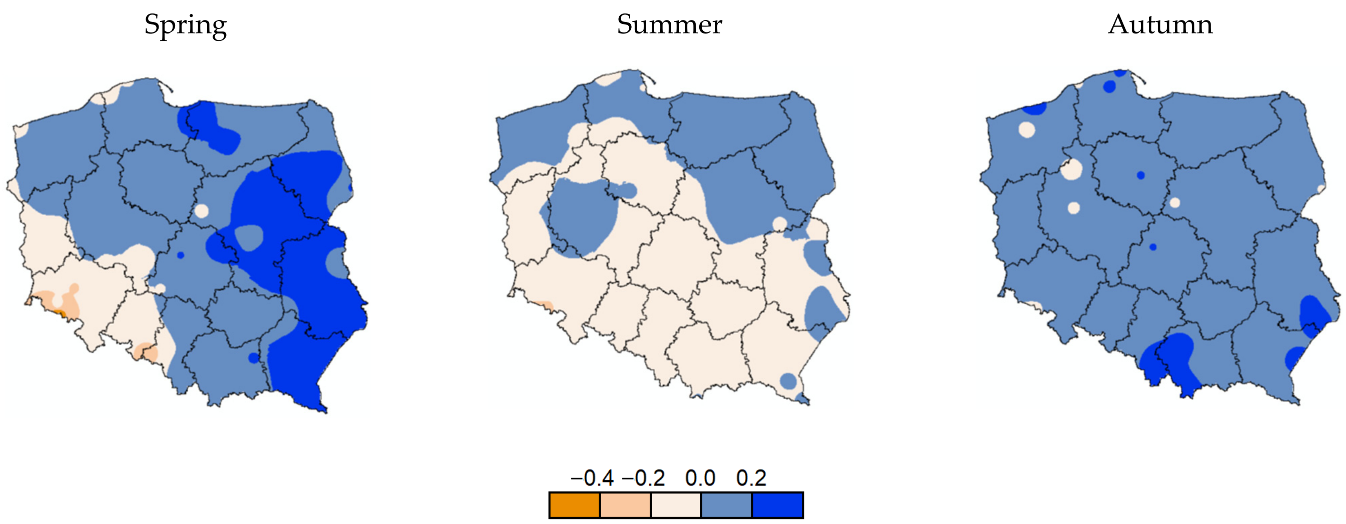

Figure 7. Correlation coefficient calculated for the linear trend of *SPI-3* in spring, summer and autumn. Years 1951–2020.

In summer, a negative *SPI-3* trend is visible in the majority of the country, including the entire southern and central Poland. In the autumn season, a negative *SPI-3* trend is confirmed only in single locations, mainly in the central part of the country. A significant (at a level of $\alpha < 0.1$) positive *SPI-3* trend was found in the spring season in east Poland, and also in autumn, but only in single places in the south and north of Poland.

3.2. AAMDr Index–Temporal Distribution

The area of the country affected by meteorological drought (*AAMDr*), calculated on the basis of *SPI-3*, varied and fluctuated on average from 11.1% in summer to 18.9% in spring (Table 2).

Extreme drought affected on average only 2.4% of Poland's area: in autumn, extreme drought affected the largest area, 3.9%; in spring, it affected 2.1%; and in summer it affected 1.1% of Poland's area. The area affected by severe drought was on average 1.7%

bigger than the area affected by extreme drought. The area affected by severe drought in 1951–2020 oscillated between 3.4% in summer and 4.7% of Poland's area in the spring season. Moderate drought affected, on average, the largest part of Poland's area in the spring season (12.1%). In spring, the area affected by drought was approx. 1.5–2 times bigger than in summer (6.6%) and autumn (7.7%). The biggest standard deviation was found for *AAMDr* of moderate intensity in both spring and summer, when it amounted to 13.7% and 10.3%, respectively. The situation looked different in the case of the autumn season because extreme drought was the most variable (sd = 13.9%), followed by moderate drought (sd = 11.6%). For *AAMDr* of extreme and severe intensity, in the spring season a significant (at a level of $\alpha < 0.05$) linear trend was found; the Pearson correlation coefficients were -0.297 for extreme drought and -0.247 for severe drought. It can be seen that the area of Poland affected by meteorological drought also decreases year by year in autumn ($r = -0.228$, $\alpha < 0.1$).

Table 2. Characteristics of Poland's area affected by meteorological drought (*AAMDr*), determined on the basis of *SPI-3*. Years 1951–2020.

Season	Intensification of Meteorological Drought	Characteristics			
		$\bar{x}$ (%)	sd (%)	Max (%)	r for a Linear Trend
Spring	ed	2.1	6.0	34.6	–0.297 **
	vd	4.7	7.7	38.7	–0.247 **
	md	12.1	13.7	57.0	–0.067
	MDr (ed + vd + md)	18.9	23.3	83.8	–0.198
Summer	ed	1.1	4.0	26.4	0.137
	vd	3.4	8.9	42.1	0.115
	md	6.6	10.3	37.7	0.024
	MDr (ed + vd + md)	11.1	21.2	93.4	0.085
Autumn	ed	3.9	13.9	76.7	–0.111
	vd	4.2	9.7	50.1	–0.088
	md	7.7	11.6	57.0	–0.182
	MDr (ed + vd + md)	15.8	27.6	99.5	–0.228 *

Notes: ed–extreme drought, vd–severe drought, md–moderate drought, *MDr*–meteorological drought, $\bar{x}$–mean (%), sd–standard deviation (%), max–the highest value in the multi-year period (%), r–Pearson correlation coefficient, ** significant at $\alpha \leq 0.05$, * significant at $\alpha \leq 0.1$.

The percentage area of Poland that is affected by meteorological drought in spring fluctuated from 0% in 1962, 1967, 1994, 1995, 1997, 1998, 2009, 2010 and 2014 to as much as 83.8% in 1959 (Figure 8).

The highest *AAMDr* values with the extreme intensity of droughts were recorded in 1953 and 1974, when they amounted to 34.6% and 31.1% of the area of Poland, respectively. *AAMDr* of severe intensity amounted to 38.7% in 1959 and 24.4% in 1974. The highest values of *AAMDr*, >40% country's area, were related to moderate drought. *AAMDr* values of >40% occurred in four years: 1993 (57.0%), 1976 (47.6%), 1957 (45.9%) and 2018 (40.1%).

The value of *AAMDr* in summer fluctuated from 0% in 1956, 1960, 1965, 1974, 1980, 1981, 2000, 2001, 2006, 2010, 2011 and 2016 to as much as 93.4% in 1992 (Figure 8). Apart from 1992, *AAMDr* was also >70% in another three years: 2015 (84.1%), 1994 (73.8%) and 1983 (73.0%). The biggest area of Poland affected by extreme drought was found for the following years: 2015 (26.4%), 1983 (14.7%) and 1992 (13.5%). Severe drought affected the largest area in 1992 (42.1%), 1994 (36.0%), 1983 (33.2%) and 2015 (32.9%), whereas the area with moderate drought was largest in 1992 (37.7%), 1976 (37.4%) and 2019 (36.4%).

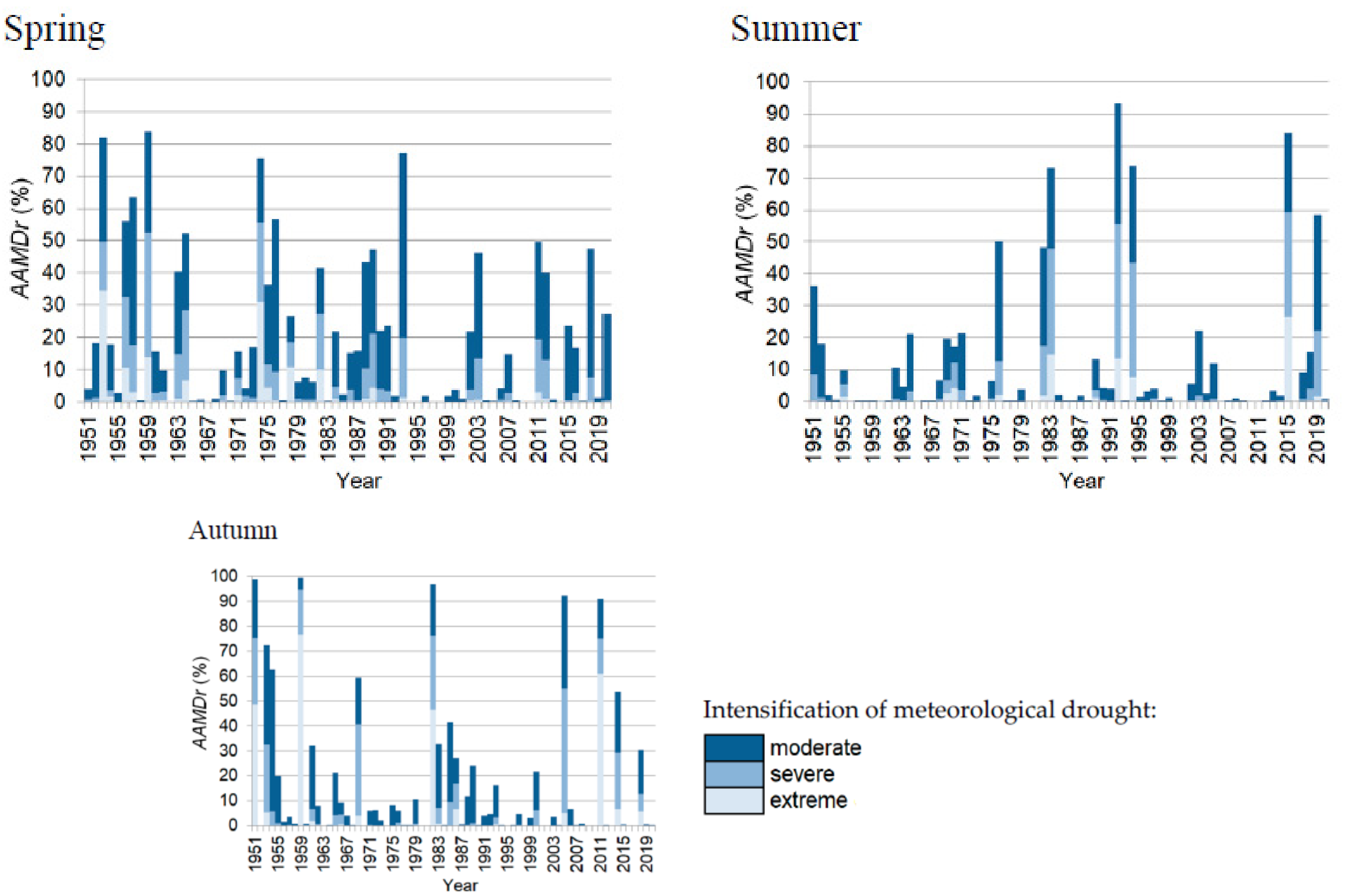

Figure 8. Variations in Poland's area affected by meteorological drought (*AAMDr*) of varying intensity, determined based on *SPI-3* in spring, summer and autumn. Years 1951–2020.

The largest area of the country, >90%, affected by meteorological drought in autumn was recorded in 5 years: 1959 (99.5%), 1951 (98.9%), 1982 (96.8%), 2005 (92.4%) and 2011 (91.0%) (Figure 8). The *AAMDr* index of extreme intensity was highest in 1959 (76.7%), followed by 2011 (60.8%), 1951 (48.7%) and 1982 (46.5%). In turn, the largest area of Poland affected by severe drought was recorded in 2005 (50.1%) and 1969 (36.6%). The largest area of Poland affected by moderate drought was recorded in 1954 (57.0%), 1953 (40.0%) and 2005 (37.2%).

3.3. Dependence of AAMDr on SPI-3

Examination of the dependence of the country's area affected by meteorological drought (*AAMDr*) on *SPI-3* showed a significant ($\alpha < 0.01$) and close relationship between the analyzed indicators in each of the analyzed seasons (Table 3, Figure 9).

The *SPI-3* index explained the variability of *AAMDr* in spring, from approx. 69%, when *SPI-3* was within the range from –2.2 to 2.4, to as much as approx. 88%, when *SPI-3* was within the range of from –2.2 to 0. The Student's *t*-test and Snedecor's F-distribution values that were calculated for the linear regression equations ranged respectively from –12.2 to –17.5 and from 149.1 to 304.8.

In summer, as in spring, the closest relationship between *AAMDr* and *SPI-3* was found when *SPI-3* ranged from −2.4 to 0. The coefficient of determination calculated for this equation amounted to as much as 92.1%; the value of the Student's *t*-test was −18.2, and the value of Snedecor's F-distribution was 329.6. In autumn, the dependence of *AAMDr* on *SPI-3* was negative, significant at a level of $\alpha < 0.01$, as in the case of spring and summer. R^2 ranged from approx. 67% to 90%, whereas the value of the Student's *t*-test fluctuated from −11.7 to −18.2 and the value of Snedecor's F-distribution ranged from 136 to 332.7.

MAE ranged from 6.6% to 10.4% for spring, from 5.5% to 10.1% for summer and from 8.2% to 12.5% for autumn. The highest negative regression coefficient for the dependence of *AAMD*r on *SPI-3*, when *SPI-3* ranged from the minimum value to 0, was found for the summer season (−39.62) and was lowest for the autumn season (−38.25).

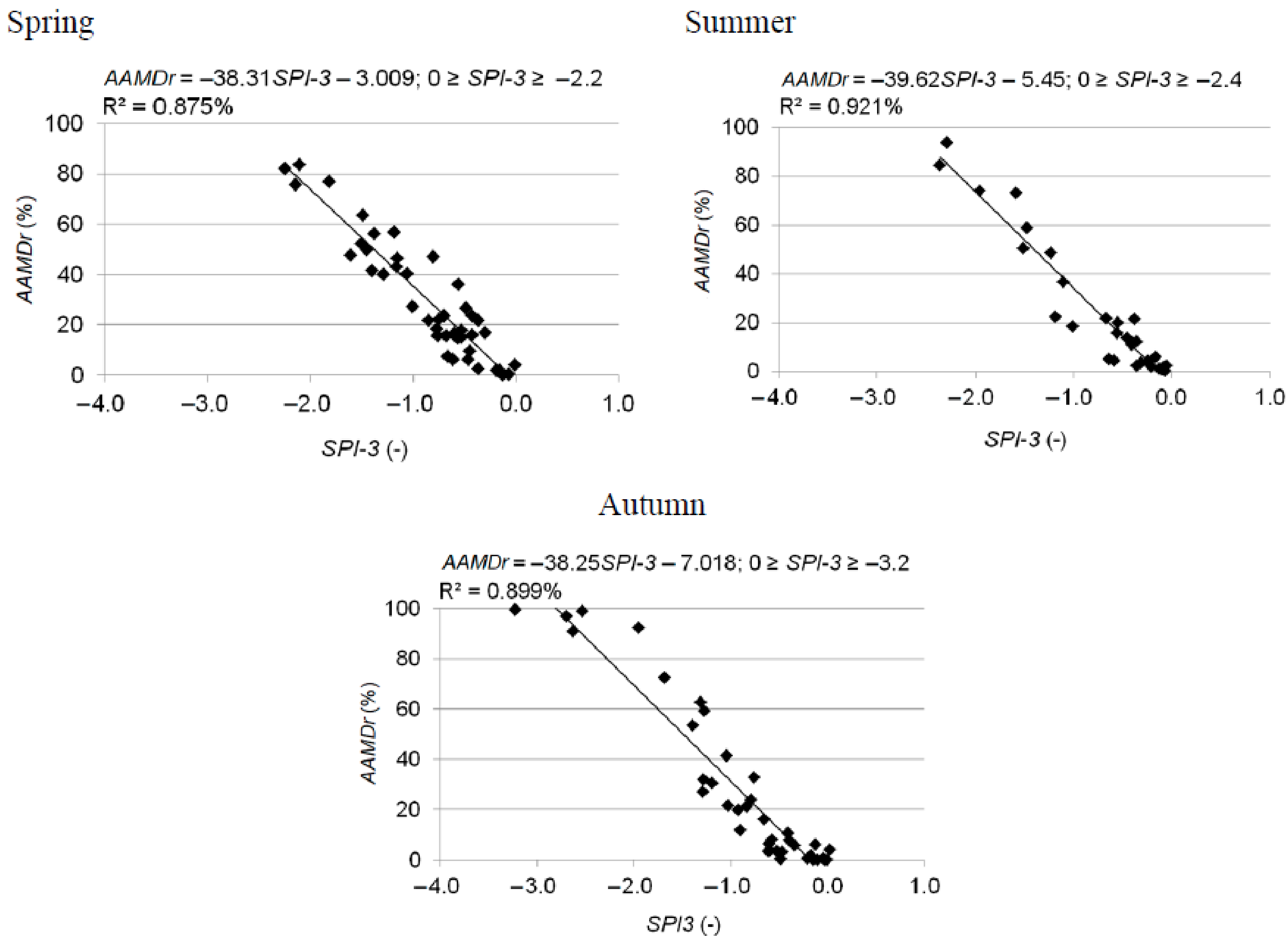

Figure 9. Dependence on *SPI-3* of Poland's area affected by meteorological drought (*AAMDr*), ranging from the minimum value to 0 in spring, summer and autumn. Years 1951–2020.

Table 3. Dependence on *SPI-3* of Poland's area affected by meteorological drought (*AAMDr*) in its selected ranges in spring, summer and autumn. Years 1951–2020.

			Spring			
SPI-3	N	R^2	*F*	*t*	*MAE*	α
–2.2 ÷ 2.4	70	0.686	149.1	–12.2	10.4	0.01
–2.2 ÷ 1.5	66	0.773	218.0	–14.8	9.6	0.01
–2.2 ÷ 1.0	64	0.800	248.7	–15.7	9.0	0.01
–2.2 ÷ 0.5	55	0.852	304.8	–17.5	7.8	0.01
–2.2 ÷ –0.0	43	0.875	287.2	–16.9	6.6	0.01
–2.2 ÷ –0.5	32	0.849	169.2	–13.0	7.1	0.01
			Summer			
SPI-3	N	R^2	*F*	*t*	*MAE*	α
–2.4 ÷ 1.9	70	0.645	123.8	–11.1	10.1	0.01
–2.4 ÷ 1.5	68	0.682	141.4	–11.9	9.8	0.01
–2.4 ÷ 1.0	59	0.769	190.5	–13.8	8.6	0.01
–2.4 ÷ 0.5	52	0.814	219.4	–14.8	8.1	0.01

Table 3. *Cont.*

–2.4 ÷ –0.0	30	0.921	329.6	–18.2	5.5	0.01
–2.4 ÷ –0.5	15	0.902	119.0	–10.9	7.6	0.01
			Autumn			
SPI-3	N	R^2	*F*	*t*	*MAE*	α
–3.2 ÷ 2.5	70	0.666	136.0	–11.7	12.5	0.01
–3.2 ÷ 1.5	67	0.758	203.8	–14.3	11.7	0.01
–3.2 ÷ 1.0	64	0.781	221.6	–14.9	11.4	0.01
–3.2 ÷ 0.5	50	0.858	290.4	–17.0	9.7	0.01
–3.2 ÷ –0.0	39	0.899	332.7	–18.2	8.2	0.01
–3.2 ÷ –0.5	27	0.886	191.4	–13.9	9.2	0.01

Notes: N–degrees of freedom, R^2–coefficient of determination (%), *F*–Snedocor test, *t*–Student's *t*-test, α–significance level, *MAE*–mean absolute error (%).

4. Discussion

Meteorological drought is an important atmospheric phenomenon which limits agricultural development in many countries, causing, e.g., reduced yields of cultivated plants [33,48–51]. Therefore, *MDr* remains relevant, despite the fact that it has been the subject of many research studies [35,42,52]. However, it is still difficult to predict meteorological drought even in countries with very good weather monitoring [53,54]. Examination of meteorological drought is usually conducted after the event on the basis of historical materials [23,55,56].

In this paper, *MDr* was identified by means of the standardized precipitation index (*SPI*), whose advantages are its ability to determine drought intensity in three classes (extreme, severe and moderate) and the possibility of comparing results calculated for periods of different durations. This paper shows that in 1951–2020 the number of years with meteorological drought in Poland varied in particular decades and depended on the analyzed season. The research by [57] conducted for the years 1971–2015 confirms the occurrence of meteorological drought in Poland in the years in which it was also proved in this paper: 1974, 1992, 2005 and 2015. Ref. [56] showed the occurrence of drought in central Poland, on average, every 5 years, including extreme drought in only 2 years: 1982 and 1989. On the other hand, [21] identified extreme drought only in 1992. Ref. [50], with the use of the *SPI-3* index, identified *MDr* in at least 3 of the 6 analyzed regions of Poland in the April–June season only in 1976. Similar to the present paper, Ref. [58] identified *MDr* of extreme and severe intensity in the growing season in 1969, 1982, 1992, 1994, 1996, 1997, 2006, 2009 and 2015. The slightly different *MDr* frequency that was found in the current paper, in comparison with the above-mentioned works, is mainly the result of the following: examination of a different, usually shorter, multi-annual period; a different period, most often a month rather than a season; and different regions of Poland. By means of *SPI*, researchers identified fewer periods of the occurrence of meteorological drought in Poland than with the use of other indicators, such as Selyaninov's hydrothermal coefficient or the relative precipitation index [56,58,59], which may be explained by the stricter criteria of the analyzed index.

Based on the trend of *SPI-3*, this research study shows that in the coming years in Poland increased droughts are likely, mainly in spring and summer. At the same time, locally in the east of Poland, drought intensity may decrease in spring. These results detail general drought trend directions determined for Europe [12,14,22,23].

The occurrence of meteorological drought in Poland has considerable spatial diversity; therefore, assessing drought on the basis of averaged values of indicators for the whole area of Poland, or even for a given region, seems to be incomplete and insufficient [58]. In Poland, drought occurrence is variable, and therefore, with the exception of mountain regions in the south of the country, it is not possible to definitively indicate areas which would not be exposed to the risk of drought. Ref. [60] found that extremely dry periods occurred more often in the western part of the investigated region, and moderately dry periods were more frequent in the eastern part of Poland. On the other hand, and similar to the current paper, Ref. [61] most frequently identified extreme drought in northwest and central-east Poland and moderate drought in central and southeast Poland. The spatial distribution of drought in Poland changes depending on the applied indicator and the adopted criterion of selecting periods with a given intensity of meteorological drought. Moreover, the different distribution of the frequency of drought in 1951–2020 that was found by other authors [58,60] is a result of the fact that this paper adopted a different reference period, i.e., 1990–2020.

In 1951–2020, on average, the largest area of the country affected by meteorological drought (*AAMDr*) was identified in spring (18.9%), followed by autumn. On the other hand, the smallest area of the country with meteorological drought was identified in summer; in spring the drought-affected area was approx. 8% bigger than in summer. The research by [23] showed that, in the spring season, precipitation deficits affected, on average, 33% of Poland's area, i.e., 14.1% more than shown in this study. In Poland, there is a shift in the occurrence of meteorological drought from summer to spring and autumn [47]. Most probably, this is an effect of clearly accelerated climate warming in the winter–spring season of the last 35 years [62] and the progressive disappearance of snow cover in winter, which results in declining water levels in soil in spring [63,64]. The occurrence of meteorological drought is a result of increasingly common short-lasting storms, often separated by long, dry periods, thus leading to atmospheric drought [65]. The research on meteorological drought contributes to improved drought monitoring, which fits in with implementation of some of the aims of the common agricultural policy in the European Union, i.e., supporting sustainable management of natural resources and fighting against climate change [66].

5. Conclusions

The paper shows that meteorological drought (*MDr*) in Poland occurs more frequently in spring and autumn (every 4–5 years) than in summer (every 7 years). In 1951–2020, meteorological drought did not occur with the same frequency across Poland. In the spring season, *MDr* was most often recorded in the east and north (every 3–4 years); in summer, *MDr* most frequently occurred in north and central-west Poland (every 5–7 years); in autumn, *MDr* was most often recorded in the south and northwest of Poland (every 3–5 years).

Extreme drought (*SPI-3* ≤ -2.0) in spring across the whole of Poland occurred in 3 of the 70 examined years: 1953, 1959 and 1974. In summer, extreme drought was recorded in two years: 1992 and 2015. In autumn, extreme drought occurred in five years: 1951, 1959, 1982, 2005 and 2011. In the areas with *SPI-3* ≤ -2.0, precipitation was below the average, mainly $\leq$50% of the climatic norm (ΔPr), locally even $\leq$25%, which happened in the autumn season in three years: 1951, 1959 and 2011. On the other hand, air temperature values were below or above the climatic norm (ΔTa) and mainly ranged from -1.0 to 1.0 °C, whereas ≤ -2.0 °C occurred only in 1959 in the autumn season.

In 1951–2020, the area of the country affected by meteorological drought (*AAMDr*), determined based on the *SPI-3* index, amounted on average to 18.9% in spring, 11.1% in summer and 15.8% in autumn. *AAMDr* of extreme intensity ranged from 1.1% to 3.9%; the area affected by severe drought fluctuated between 3.4% and 4.7%; and the area affected by moderate drought ranged from 6.6% to 12.1%. The values of *AAMDr* $\geq$75% were calculated for the years when *SPI-3* amounted to ≤ -2.0. The spring season of 1993 was an exception, because as much as 57% of the country's area was affected by moderate drought. In the autumn seasons of 1951 and 1959, almost all of the country's area was affected by drought: in these years, respectively, extreme drought affected approx. 49% and 77% of Poland's area; severe drought affected approx. 27% and 18%; and moderate drought affected approx. 24% and 5% of Poland's area.

The paper proved a significant (at a level of $\alpha < 0.01$) negative relationship between *AAMDr* and *SPI-3*; the closest relationship was found with *SPI-3* within the range from the minimum value to 0. R^2 calculated for the regression equations ranged from approx. 88% to 92% and the values of Snedecor's *F*-distribution ranged from approx. 287 to 333.

A positive *SPI-3* trend was found in the areas of Poland with the highest frequency of meteorological drought in all of the examined seasons; this means that the risk of intensification of the analyzed phenomenon in these regions becomes reduced year by year. However, after considering scientific reports about a significant increase in air temperature in the last 30 years in Poland, it can be assumed that *MDr* will most probably intensify and expand.

The standardized precipitation index determined for the seasons makes it possible to evaluate short- and medium-term variations in meteorological drought in Poland in time and in space and also its intensity in three classes: extreme, severe and moderate. The research on the dynamics of meteorological drought change should be continued and even broadened with long periods of half a year, one year and two years, as the climatic instability that climatologists predict will occur by 2050 may significantly influence its development and intensity, which in turn will affect farming systems and agrarian structure in Poland.

The obtained results could be useful for managing climatic risk and developing regional and local agriculture adaptation plans that are aimed at mitigating climate change effects.

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References

1. Łupikasza, E. The climatology of air-mass and frontal extreme precipitation. In *Study of Meteorological Data in Europe*, 1st ed.; Springer International Publishing: Cham, Switzerland, 2016; p. 313. [CrossRef]
2. Niedźwiedź, T.; Łupikasza, E. Atmospheric circulation in the investigations of the Polish climatologists. *Przegl. Geofiz.* **2019**, *64*, 107–166. [CrossRef]
3. Bartoszek, K.; Baranowska, A.; Kukla, Ł.; Skowera, B.; Węgrzyn, A. Spatiotemporal assessment and meteorological determinants of atmospheric drought in agricultural areas of East-Central Poland. *Agronomy* **2021**, *11*, 2405. [CrossRef]
4. King, M.P.; Yu, E.; Sillmann, J. Impact of strong and extreme El Niños on European hydroclimate. *Tellus A: Dyn. Meteorol. Oceanogr.* **2020**, *72*, 1, 1–10. [CrossRef]
5. Nguyen, P.-L.; Min, S.-K.; Kim, Y.-H. Combined impacts of the El Niño-Southern Oscillation and Pacific Decadal Oscillation on global droughts assessed using the standardized precipitation evapotranspiration index. *Int. J. Climatol.* **2021**, *41*, E1645–E1662. [CrossRef]
6. Przybylak, R.; Maszewski, R. Atmospheric circulation variability in the Bydgosko-Toruński Region in the period 1881–2005. *Acta Agrophys.* **2009**, *171*, 427–447. (In Polish)
7. Piotrowski, P. Circular conditions of spring droughts in Poland. In *The Climate of Poland against the Background of the Climate of Europe. Thermal and Rainfall Conditions*, 1st ed.; Bednarz, E., Ed.; Bogucki Wydaw. Nauk.: Poznań, Poland, 2010; pp. 147–158. (In Polish)
8. Lorenc, H.; Gąsiorowska, E.; Laskowska, A.; Strzelczak, A.; Żórawska, K. Initial assessment of the drought in 2000. In *Present and Future Requirements for Agrometeorological Information, Proceedings of the International Conference, Poznań-Sielinko, Poland, 11–15 September 2000*; IMGW: Warszawa, Poland, 2000; pp. 14–27.
9. Niedzielski, T. Is there any teleconnection between surface hydrology in Poland and El Niño/Southern Oscillation? *Pure Appl. Geophys.* **2011**, *168*, 871–886. [CrossRef]
10. Spinoni, J.; Vogt, J.V.; Naumann, G.; Barbosa, P.; Dosio, A. Will drought events become more frequent and severe in Europe? *Int. J. Climatol.* **2018**, *38*, 1718–1736. [CrossRef]
11. EEA. Meteorological and Hydrological Droughts in Europe. 2021. Available online: https://www.eea.europa.eu/data-and-maps/indicators/river-flow-drought-3/assessment (accessed on 20 August 2022).

12. Song, X.; Song, Y.; Chen, Y. Secular trend of global drought since 1950. *Environ. Res. Lett.* **2020**, *15*, 094073. [CrossRef]
13. McCabe, G.J.; Wolock, D.M. Variability and trends in global drought. *Earth Space Sci.* **2015**, *2*, 223–228. [CrossRef]
14. IPCC. Summary for Policymakers. In *Climate Change: The Physical Science Basis. Contribution of Working Group I to the Sixth As-sessment Report of the Intergovernmental Panel on Climate Change*; Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., et al., Eds.; Cambridge University Press: Cambridge, UK, 2021; Available online: https://report.ipcc.ch/ar6wg1/pdf/IPCC_AR6_WGI_SPM.pdf (accessed on 15 June 2022).
15. Ionita, M.; Nagavciuc, V.; Kumar, R.; Rakovec, O. On the curious case of the recent decade, mid-spring precipitation deficit in central Europe. *npj Clim. Atmos. Sci.* **2020**, *3*, 49. [CrossRef]
16. Blauhut, V.; Gudmundsson, L.; Stahl, K. Towards pan-European drought risk maps: Quantifying the link between drought indices and reported drought impacts. *Environ. Res. Lett.* **2015**, *10*, 014008. [CrossRef]
17. Spinoni, J.; Naumann, G.; Vogt, J.V.; Barbosa, P. *Meteorological Droughts in Europe: Events and Impacts–Past Trends and Future Projections*; EUR 27748 EN; Publications Office of the European Union: Luxembourg, 2016; p. 134. [CrossRef]
18. van der Velde, M.; Baruth, B.; Bussay, A.; Ceglar, A.; Condado, S.G.; Karetsos, S.; Lecerf, R.; Lopez, R.; Maiorano, A.; Nisini, L.; et al. In-season performance of European Union wheat forecasts during extreme impacts. *Sci. Rep.* **2018**, *8*, 15420. [CrossRef] [PubMed]
19. Eludoyin, A.O.; Eludoyin, O.M.; Eslamian, S. Drought Mitigation Practices. In *Handbook of Drought and Water Scarcity: Management of Drought and Water Scarcity*, 1st ed.; Eslamian, S., Eslamian, F.A., Eds.; CRC: Boca Raton, FL, USA, 2018; Chapter 19; Volume 3, pp. 393–404.
20. Hamdy, A.; Trisorio-Liuzzi, G. Drought planning and drought mitigation measures in the Mediterranean region. *Options Méditerranéennes* **2009**, *80*, 235–239.
21. Łabędzki, L. Estimation of local drought frequency in central Poland using the standardized precipitation index SPI. *Irrig. Drain.* **2007**, *56*, 67–77. [CrossRef]
22. Kalbarczyk, R.; Kalbarczyk, E. Precipitation variability, trends and regions in Poland: Temporal and spatial distribution in the years 1951–2018. *Acta Geogr. Slov.* **2021**, *61*, 41–71. [CrossRef]
23. Kalbarczyk, R.; Kalbarczyk, E. Spring precipitation deficiency in Poland and its temporal and spatial variability in the context of agricultural needs. *Agronomy* **2022**, *12*, 158. [CrossRef]
24. Hlavinka, P.; Trnka, M.; Semeradova, D.; Dubrovský, M.; Žalud, Z.; Možný, M. Effect of drought on yield variability of key crops in Czech Republic. *Agric. For. Meteorol.* **2009**, *149*, 431–442. [CrossRef]
25. Kalbarczyk, R. Temporal and spatial diversity of the occurrence of atmospheric drought in Poland (1966-2005) and its effect on yield of pickling cucumber (*Cucumis sativus* L.). *Span. J. Agric. Res.* **2010**, *8*, 1147–1162. [CrossRef]
26. Kalbarczyk, R.; Kalbarczyk, E.; Raszka, B. Risk to onion (*Allium cepa* L.) field cultivation in Poland from precipitation deficiency. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2011**, *39*, 214–218. [CrossRef]
27. Kuśmierek-Tomaszewska, R.; Żarski, J.; Dudek, S. Assessment of irrigation needs in sugar beet (*Beta vulgaris* L.) in temperate climate of Kujawsko-Pomorskie region (Poland). *Agronomy* **2019**, *9*, 814. [CrossRef]
28. Kubiak-Wójcicka, K.; Machula, S. Influence of climate changes on the state of water resources in Poland and their usage. *Geosciences* **2020**, *10*, 312. [CrossRef]
29. Sawicka, B.; Barbaś, P.; Pszczółkowski, P.; Skiba, D.; Yeganehpoor, F.; Krochmal-Marczak, B. Climate changes in southeastern Poland and food security. *Climate* **2022**, *10*, 57. [CrossRef]
30. Łabędzki, L. Categorical forecast of precipitation anomaly using the Standardized Precipitation Index SPI. *Water* **2017**, *9*, 8. [CrossRef]
31. Agricultural Drought Monitoring System. Available online: https://susza.iung.pulawy.pl/en/index/ (accessed on 20 August 2022).
32. The act on insurance of agricultural crops and livestock. *J. Laws* **2019**, 477. Available online: https://eli.sejm.gov.pl/eli/DU/2019/477/ogl (accessed on 20 August 2022). (In Polish).
33. Łabędzki, L.; Bąk, B. Indicator-based monitoring and forecasting water deficit and surplus in agriculture in Poland. *Ann. Wars. Univ. Life Sci.* **2015**, *47*, 355–369. [CrossRef]
34. Hänsel, S. Changes in the characteristics of dry and wet periods in Europe (1851–2015). *Atmosphere* **2020**, *11*, 1080. [CrossRef]
35. Liu, C.; Yang, C.; Yang, Q.; Wang, J. Spatiotemporal drought analysis by the standardized precipitation index (SPI) and standardized precipitation evapotranspiration index (SPEI) in Sichuan Province, China. *Sci. Rep.* **2021**, *11*, 1280. [CrossRef]
36. Salimi, H.; Asadi, E.; Darbandi, S. Meteorological and hydrological drought monitoring using several drought indices. *Appl. Water Sci.* **2021**, *11*, 11. [CrossRef]
37. McKee, T.B.; Doesken, N.J.; Kleist, J. The relationship of drought frequency and duration to time scale. In Proceedings of the Eighth Conference on Applied Climatology, Anaheim, CA, USA, 17–22 January 1993; American Meteorological Society: Boston, MA, USA, 1993; pp. 179–184.
38. McKee, T.B.; Doesken, N.J.; Kleist, J. Drought monitoring with multiple time scales. In Proceedings of the Ninth Conference on Applied Climatology, Dallas, TX, USA, 15–20 January 1995; American Meteorological Society: Boston, MA, USA, 1995; pp. 233–236.
39. Svoboda, M.D.; Fuchs, B.A.; Poulsen, C.C.; Nothwehr, J.R. The drought risk atlas: Enhancing decision support for drought risk management in the United States. *J. Hydrol.* **2015**, *526*, 274–286. [CrossRef]

40. Zhang, L.; Jiao, W.; Zhang, H.; Huang, C.; Tong, Q. Studying drought phenomena in the Continental United States in 2011 and 2012 using various drought indices. *Remote Sens. Environ.* **2017**, *190*, 96–106. [CrossRef]
41. Leasor, Z.T.; Quiring, S.M.; Svoboda, M.D. Utilizing objective drought severity thresholds to improve drought monitoring. *J. Appl. Meteorol. Clim.* **2020**, *59*, 455–475. Available online: https://digitalcommons.unl.edu/droughtfacpub/171 (accessed on 20 August 2022). [CrossRef]
42. Caloiero, T.; Caroletti, G.N.; Coscarelli, R. IMERG-based meteorological drought analysis over Italy. *Climate* **2021**, *9*, 65. [CrossRef]
43. Mathbout, S.; Lopez-Bustins, J.A.; Royé, D.; Martin-Vide, J. Mediterranean-scale drought: Regional datasets for exceptional meteorological drought events during 1975–2019. *Atmosphere* **2021**, *12*, 941. [CrossRef]
44. Svoboda, M.; Hayes, M.; Wood, D.A. *Standardized Precipitation Index User Guide*; WMO-No. 1090; World Meteorological Organization: Geneva, Switzerland, 2012; p. 24.
45. Cammalleri, C.; Spinoni, J.; Barbosa, P.; Toreti, A.; Vogt, J.V. The effects of non-stationarity on SPI for operational drought monitoring in Europe. *Int. J. Clim.* **2021**, *42*, 3418–3430. [CrossRef]
46. Kömüşcü, A.U. Homogeneity analysis of long-term monthly precipitation data of Turkey. *Fresenius Environ. Bull.* **2010**, *19*, 1220–1230.
47. Ziernicka-Wojtaszek, A.; Kopcińska, J. Variation in atmospheric precipitation in Poland in the years 2001–2018. *Atmosphere* **2020**, *11*, 794. [CrossRef]
48. Reinermann, S.; Gessner, U.; Asam, S.; Kuenzer, C.; Dech, S. The effect of droughts on vegetation condition in Germany: An analysis based on two decades of satellite Earth observation time series and crop yield statistics. *Remote Sens.* **2019**, *11*, 1783. [CrossRef]
49. Jiménez-Donaire, M.; Tarquis, A.; Giráldez, V. Evaluation of a combined drought indicator and its potential for agricultural drought prediction in southern Spain. *Nat. Hazards Earth Syst. Sci.* **2020**, *20*, 21–33. [CrossRef]
50. Oleksiak, T.; Spyroglou, I.; Pacoń, D.; Matysik, P.; Pernisová, M.; Rybka, K. Effect of drought on wheat production in Poland between 1961 and 2019. *Crop Sci.* **2022**, *62*, 728–743. [CrossRef]
51. Rolbiecki, R.; Yücel, A.; Kocięcka, J.; Atilgan, A.; Marković, M.; Liberacki, D. Analysis of SPI as a drought indicator during the maize growing period in the Çukurova Region (Turkey). *Sustainability* **2022**, *14*, 3697. [CrossRef]
52. Zeng, Z.; Wu, W.; Li, Z.; Zhou, Y.; Huang, H. Quantitative assessment of agricultural drought risk in Southeast Gansu Province, Northwest China. *Sustainability* **2019**, *11*, 5533. [CrossRef]
53. Ihinegbul, C.; Ogunwumi, T. Multi-criteria modelling of drought: A study of Brandenburg Federal State, Germany. *Model. Earth Syst. Environ.* **2021**, *8*, 2035–2049. [CrossRef]
54. Vicente-Serrano, S.M.; Domínguez-Castro, F.; Reig, F.; Beguería, S.; Tomas-Burguera, M.; Latorre, B.; Peña-Angulo, D.; Noguera, I.; Rabanaque, I.; Luna, Y.; et al. A near real-time drought monitoring system for Spain using automatic weather station network. *Atmos. Res.* **2022**, *271*, 106095. [CrossRef]
55. Przybylak, R.; Oliński, P.; Koprowski, M.; Filipiak, J.; Pospieszyńska, A.; Chorążyczewski, W.; Puchałka, R.; Dąbrowski, H.P. Droughts in the area of Poland in recent centuries in the light of multi-proxy data. *Clim. Past* **2020**, *16*, 627–661. [CrossRef]
56. Araźny, A.; Bartczak, A.; Maszewski, R.; Krzemiński, M. The influence of atmospheric circulation on the occurrence of dry and wet periods in Central Poland in 1954–2018. *Theor. Appl. Clim.* **2021**, *146*, 1079–1095. [CrossRef]
57. Bąk, B.; Kubiak-Wójcicka, K. Impact of meteorological drought on hydrological drought in Toruń (central Poland) in the period of 1971–2015. *J. Water Land Dev.* **2016**, *32*, 3–12. [CrossRef]
58. Szyga-Pluta, K. Variability of drought occurrence during growing season in Poland in years 1966–2015. *Przegl. Geofiz.* **2018**, *63*, 51–67. (In Polish)
59. Baryła, A.; Hewelke, E.; Stańczyk, T.; Ptach, W. Relative precipitation indexes in the Puczniew area. *Sci. Rev. Eng. Env. Sci.* **2016**, *72*, 156–166. (In Polish)
60. Radzka, E. The Assessment of atmospheric drought during vegetation season (according to standardized precipitation index SPI) in central-eastern Poland. *J. Ecol. Eng.* **2015**, *16*, 87–91. [CrossRef]
61. Łabędzki, L.; Bąk, B. Differentiation of the atmospheric drought index SPI in the vegetation period in Poland. *Woda-Śr.-Obsz. Wiej.* **2004**, *4*, 111–122. (In Polish)
62. Żmudzka, E. Contemporary Changes of climate of Poland. *Acta Agrophys.* **2009**, *13*, 555–568. (In Polish)
63. Szwed, M.; Pińskwar, I.; Kundzewicz, Z.W.; Graczyk, D.; Mezghani, A. Changes of snow cover in Poland. *Acta Geophys.* **2017**, *65*, 65–76. [CrossRef]
64. Karamuz, E.; Romanowicz, R.J. Temperature changes and their impact on drought conditions in winter and spring in the Vistula Basin. *Water* **2021**, *13*, 1973. [CrossRef]
65. Wartalska, K.; Kotowski, A. Model hyetographs of short-term rainfall for Wrocław in the perspective of 2050. *Atmosphere* **2020**, *11*, 663. [CrossRef]
66. The Common Agricultural Policy at a Glance. Available online: https://agriculture.ec.europa.eu/common-agricultural-policy/cap-overview/cap-glance_en#title (accessed on 20 August 2022).