INTRODUCTION

Mild frosts are natural phenomena which are the most frequent during transitions between seasons of the year. These frosts occur when the average 24-hour air temperature is positive but the minimum temperature drops below 0°C (Szyga-Pluta 2017, Witeska 2011). There are several classification criteria of such frosts. They can be divided by season into spring and autumn frosts. The spring frosts occur from April to mid-June, and the autumn frosts are recorded at the turn of summer and autumn (Witeska 2011). According to the reason leading to the occurrence of these frosts, they can be classified as convection frosts following an arrival of cool air, radiation frosts appearing due to heat radiation from the ground to the atmosphere, and advection-radiation frosts which are a blend of both the above-mentioned types (Jerzak 2011, Doroszewski et al. 2013). In terms of height at which they occur, frosts are divided into ground and high frosts (at the level of, respectively, 5 and 200 cm from the ground). Taking their intensity into account, there are light frosts (the temperature drop ranges from −0.1 to −1.9°C), moderate frosts (from −1.9 to −3.9°C), and severe frosts (lower than −3.9°C) (Niedźwiedź 2003).

The occurrence of frosts is associated with numerous factors, including the lie of the land and its cover, hydrographic network, ground type, forested and mountainous areas and the presence of higher rises (Koźmiński and Michalska 2008). The phenomenon may occur during every growing season and, despite climate warming (warmer winters), the period when such frost is likely to occur is extending. The first autumn frost may occur very early, and the latest spring frost – very late in the season (Starkel and Kundzewicz 2008), which was confirmed by Kalbarczyk (2010) and Grabowski...
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who observed that, in north-east Poland, the frost-free period is shrinking. Frosts negatively influence the plant production effects, as they cause direct and indirect damage to plants, and the extent of this damage depends on how intense the frost is (Dragańska et al. 2004). Determination of the direction of long-term changes at the regional and even local scale is of paramount importance. A hypothesis was put forward that in an age when the climate is warming, there has been a shifting in time, in a long-term period, of an occurrence of the last spring frosts and the first autumn frost events, resulting in a change in the length of the frost-free period. To this end, the analysis of the frequency of high frosts was performed, the timing of the last spring frost and first autumn frost was recorded, and frost intensity was determined in central-east Poland in 2001–2018.

MATERIALS AND METHODS

The analysis of results which were daily meteorological data obtained from seven meteorological stations located in Białowieża, Legionowo, Pułtusk, Siedlce, Szepietowo, Warsaw and Terešpol was performed. All types of high frosts were subjected to analysis: light, moderate and severe frosts recorded in spring and autumn. The structure and dates of an occurrence of these frosts were analysed, too. Time series regression analysis was conducted to study the trends of change in the frost-free period in the study area (Sobczyk 2007).

RESULTS AND DISCUSSION

The number of days with mild frosts, in addition to number of frosty days, cold and warm days, is an indicator describing thermal relationships in a given area. In Poland, the risk of mild frosts and damage to crop plants is an annual possibility for the whole country (Kossowska-Cezak 2003). The extent of damage due to frost depends on its intensity, frequency and timing. Spring frosts occurring at the turn of winter and spring is of greater concern because this is the crop sowing time followed by emergence of frost-tender seedlings, bud formation as well as blooming of fruit trees and shrubs, all of which are at risk of damage by the frost. In autumn, early frosts are far less harmful (Dudek et al. 2012).

From 2001 to 2018, the greatest number of days with frosts during the growing season (April–October) was recorded in Białowieża and Pułtusk (respectively, 285 and 216 days); conversely, it was the lowest in Warsaw and Legionowo (respectively, 129 and 216 days). At all the stations, the majority of frosts were light frosts with the percentages ranging from 55.4 to 64.4% in Białowieża and Szepietowo, respectively. The greatest percentages of moderate and severe frosts were recorded in Pułtusk (33.8%) and Siedlce (13.8%), respectively (Figure 1). Figures 2 and 3 demonstrate that at nearly all the stations, more frosts (regardless of their intensity) were recorded in spring rather than autumn. Terespol and Warsaw were exceptions, as their numbers of all types of frosts were higher in autumn than spring.

The greatest number of days with spring frosts, regardless of their intensity, was recorded at the station located in Białowieża and it amounted to 176 over the long-term period. Light, moderate and severe frost represented 55.0, 32.3 and slightly above 13.0% measurements, respectively, in the long-term study period. The lowest number of days with frosts (64) was recorded in Warsaw and Legionowo (91 days). The lowest number of days with light frost (39) as well as severe frosts, the frequency of which in the long-term period was approximately 6%, was found in Warsaw. The number of days with light frosts (21) represented 32.8% of all days with recorded frosts, and the percentage of such days was even higher than in Białowieża. In spring, there were 91 days with frosts, nearly 66% of which were light frosts, 27% were moderate frosts, and 6.5% severe frosts. At the remaining stations, the number of days with light frosts ranged from 60.7 to 67.5%, the range being 22.2 to 28.9% for moderate frosts and 7.2 to 11.8% for severe frosts (Figure 2). A higher share of light frosts in spring in central-east Poland has also been reported by Radzka et al. (2014) who point out that...
the frequency of light frosts is much higher compared with severe frosts, the occurrence of which is much more likely in spring than autumn.

The greatest number of days with autumn frosts, regardless of their type, was recorded in Terespol (111) and Białowieża (109). The respective percentages for light, moderate and severe frosts were 59 and 57%, 27 and 32% and 14 and 11%. The greatest percentage of moderate frosts was recorded in Pułtusk and Legionowo (44 and 40%, respectively), and severe frosts in Siedlce and Szepietowo (18 and 15%, respectively). In the long term (18 years), the lowest number of days with high frost was recorded in Warsaw (65 days). At the station, the percentages reflecting an occurrence of light, moderate and severe frosts were 62, 34 and barely 5%, respectively (Figure 3).

Table 1 presents the numbers of days from the beginning of the year to the moment when the last spring frost (light type) occurred. The occurrence of the last spring frost characterised by low intensity varied by station and year, and the dates ranged from 3rd April (Legionowo, 2018) to 23rd May (Białowieża and Pułtusk, 2004). The earliest dates of the last spring frost at the examined stations in the study period were recorded in 2002 and 2018. It can be noticed that at all the stations (excluding Terespol) there has been a decline in the number of days from the beginning of the year to the day when the first light autumn frost appeared. The years 2017 was an exception as there was an increase in the number of such days in Białowieża, Szepietowo and Terespol.

The first light autumn frosts occurred in the first half of October, as confirmed in the study by Radziej et al. (2014) who reported that, on average, the first frost of this intensity occurs around 11th October in the Siedlce area. In September, such frosts at few stations occurred in 2001–2005 and in 2012–2018. It is worth noting that in 2006–2011, the first autumn frosts were recorded as late as in October (table 2).

The last events of moderate frost were the most frequent in the first half of April. In early May, such frosts occurred in Białowieża, Pułtusk and Terespol in 2011. The year 2017 was exceptional in this respect, as the last moderate frost at five stations (Białowieża, Legionowo, Pułtusk, Siedlce and Warsaw) was recorded on 10th May, and on 21st April in Szepietowo and Terespol (Table 3).

As shown in table 4, the first moderate autumn frosts in the long-term study period occurred mainly in October or were not recorded at all (2006, 2008, 2012, 2017 and 2018), being recorded in Białowieża in September 2001 and 2013 (respectively, 26.09 and 30.09).

The last severe spring frost occurred every year in 2002–2007, mainly in the first half of April, excluding 2005 when, in Białowieża, Pułtusk, Siedlce and Terespol, they were recorded on 22nd or 24th April. From 2008 to 2012, no frost of this type was recorded. In the period 2012–2014, the last severe spring frosts were

![Figure 2](image2.png)  
**Figure 2.** Numbers of days by frost type during the growing season (April-July) at the stations in the long-term period

![Figure 3](image3.png)  
**Figure 3.** Numbers of days by frost type in autumn (September-October) at the stations in the long-term period
Figure 4. Trends in the number of frost-free days in the study area in 2001–2008

Table 1. Number of days, starting with the beginning of the year, with the last light spring frosts and dates of these events

| Year | Specification | Białowieża | Legionowo | Pułtusk | Siedlce | Szepietowo | Warsaw | Terespol |
|------|---------------|-------------|-----------|---------|---------|------------|--------|---------|
| 2001 | Number of days| 108         | 106       | 142     | 143     | 103        | 108    | 143     |
|      | date          | 18–04       | 16–04     | 22–05   | 23–05   | 13–04      | 18–04  | 23–05   |
| 2002 | Number of days| 98          | 99        | 97      | 99      | 98         | 98     | 99      |
|      | date          | 8–04        | 9–04      | 7–04    | 9–04    | 8–04       | 8–04   | 9–04    |
| 2003 | Number of days| 111         | 104       | 116     | 116     | 111        | 94     | 116     |
|      | date          | 21–04       | 14–04     | 26–04   | 26–04   | 21–04      | 4–04   | 26–04   |
| 2004 | Number of days| 144         | 106       | 144     | 119     | 119        | 106    | 107     |
|      | date          | 23–05       | 15–04     | 23–05   | 28–04   | 28–04      | 15–04  | 16–04   |
| 2005 | Number of days| 131         | 115       | 115     | 128     | 128        | 94     | 115     |
|      | date          | 11–05       | 25–04     | 25–04   | 8–05    | 8–05       | 4–05   | 25–04   |
| 2006 | Number of days| 104         | 106       | 106     | 106     | 106        | 106    | 106     |
|      | date          | 14–04       | 16–04     | 16–04   | 16–04   | 16–04      | 16–04  | 16–04   |
| 2007 | Number of days| 125         | 124       | 120     | 120     | 124        | 122    | 124     |
|      | date          | 5–05        | 4–05      | 30–04   | 30–04   | 4–05       | 2–05   | 4–05    |
| 2008 | Number of days| 135         | 105       | 116     | 116     | 100        | 116    |         |
|      | date          | 14–05       | 14–04     | 25–04   | 25–04   | 9–04       | 25–04  |         |
| 2009 | Number of days| 123         | 112       | 135     | 115     | 113        | 110    | 112     |
|      | date          | 3–05        | 22–04     | 15–05   | 25–04   | 23–04      | 20–04  | 22–04   |
| 2010 | Number of days| 113         | 116       | 115     | 114     | 115        | 114    | 114     |
|      | date          | 23–04       | 26–04     | 25–04   | 24–04   | 24–04      | 24–04  | 24–04   |
| 2011 | Number of days| 126         | 126       | 126     | 126     | 124        | 126    | 126     |
|      | date          | 6–05        | 6–05      | 6–05    | 6–05    | 4–05       | 6–05   | 6–05    |
| 2012 | Number of days| 135         | 94        | 105     | 94      | 102        | 109    | 109     |
|      | date          | 14–05       | 3–04      | 14–04   | 3–04    | 11–04      | 18–04  | 18–04   |
| 2013 | Number of days| 119         | 112       | 111     | 112     | 106        | 99     | 97      |
|      | date          | 29–04       | 22–04     | 21–04   | 22–04   | 16–04      | 9–04   | 7–04    |
| 2014 | Number of days| 126         | 125       | 125     | 125     | 126        | 124    | 107     |
|      | date          | 6–05        | 5–05      | 5–05    | 5–05    | 6–05       | 4–05   | 17–04   |
| 2015 | Number of days| 123         | 136       | 136     | 120     | 120        | 93     | 123     |
|      | date          | 3–05        | 16–05     | 16–05   | 30–04   | 30–04      | 3–05   | 3–05    |
| 2016 | Number of days| 95          | 117       | 114     | 112     | 119        | 93     | 94      |
|      | date          | 4–04        | 26–04     | 23–04   | 21–04   | 28–04      | 2–04   | 3–04    |
| 2017 | Number of days| 121         | 111       | 113     | 82      | 129        | 84     | 130     |
|      | date          | 1–05        | 21–04     | 23–04   | 23–03   | 9–05       | 10–05  |         |
| 2018 | Number of days| 94          | 93        | 97      | 97      | 97         | 97     | 97      |
|      | date          | 4–04        | 3–04      | 7–04    | 7–04    | 7–04       | 7–04   | 7–04    |
recorded at almost each station in early April. During the last four years, severe spring frost events occurred only in 2017 in the greater part of the study area (excluding Warsaw) and the time of this occurrence was the latest (table 5). In their work, Starlak and Kundzewicz (2008) reported that despite warmer winters, the period when frosts may occur is extending.

Severe autumn frost events were absent during the final three study years, whereas in the preceding years, they were recorded mainly in mid- or late October. The earliest occurrence of the first severe autumn frost (the end of September or early October) was observed in 2013 and 2010 (Table 6).

**CONCLUSIONS**

In 2001–2018, the greatest number of days with frosts during the growing season (April-October) was recorded in Białowieża and Pułtusk (285 and 216 days, respectively); conversely, it was the lowest in Warsaw and Legionowo (129 and 216 days, respectively). At all the stations, the majority were light frosts.
and their percentages ranged from 55.4% in Białowieża to 64.4% in Szepietowo.

At almost all stations, more frosts (regardless of their intensity) occurred in spring than autumn. The Terespol and Warsaw stations were exceptions, as their numbers of autumn light and severe frost events were higher compared with the spring. Regardless of frost intensity, the greatest number of days with spring frost events was recorded in Białowieża. Light frosts accounted for 55.0%, moderate frosts 32.3% and severe frosts slightly more than 13.0% of events in the long-term period. In The lowest number of days with light frosts was recorded in Warsaw.

The last light spring frosts occurred from 3rd to 7th April, and the earliest autumn frosts from 9th September to 27th October. The dates of moderate frost events were similar. The latest date of the last severe spring frost was 2nd May and the earliest autumn frost events took place on 30th September.

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Table 4. Number of days, starting with the beginning of the year, with the last severe spring frosts and dates of these events

| Year | Specification | Białowieża | Legionowo | Pułtusk | Siedlce | Szepietowo | Warsaw | Terespol |
|------|---------------|------------|-----------|---------|---------|------------|--------|---------|
| 2002 | Number of days | 269 | 298 | 298 | 297 |
|      | date          | 25–10     | 25–10    | 25–10   | 24–10   |
| 2003 | Number of days | 283 | 284 | 283 |
|      | date          | 11–10     | 10–10    | 11–10   | 10–10   |
| 2004 | Number of days | 292 | 290 | 290 | 292 | 290 | 292 |
|      | date          | 17–10     | 17–10    | 17–10   | 17–10   | 17–10   | 19–10 |
| 2005 | Number of days | 288 | 286 | 288 | 287 | 286 |
|      | date          | 12–10     | 14–10    | 13–10   | 12–10   | 12–10   | 12–10 |
| 2007 | Number of days | 298 | 302 | 293 | 301 | 301 | 298 |
|      | date          | 20–10     | 28–10    | 28–10   | 29–10   | 29–10   | 25–10 |

Table 5. Number of days, starting with the beginning of the year, with the first moderate autumn frosts and dates of these events

| Year | Specification | Białowieża | Legionowo | Pułtusk | Siedlce | Szepietowo | Warsaw | Terespol |
|------|---------------|------------|-----------|---------|---------|------------|--------|---------|
| 2001 | Number of days | 269 | 298 | 298 | 297 |
|      | date          | 25–10     | 25–10    | 25–10   | 24–10   |
| 2002 | Number of days | 283 | 284 | 283 |
|      | date          | 11–10     | 10–10    | 11–10   | 10–10   |
| 2003 | Number of days | 292 | 290 | 290 | 292 | 290 | 292 |
|      | date          | 17–10     | 17–10    | 17–10   | 17–10   | 17–10   | 19–10 |
| 2004 | Number of days | 288 | 286 | 288 | 287 | 286 |
|      | date          | 12–10     | 14–10    | 13–10   | 12–10   | 12–10   | 12–10 |
| 2005 | Number of days | 298 | 302 | 293 | 301 | 301 | 298 |
|      | date          | 20–10     | 28–10    | 28–10   | 29–10   | 29–10   | 25–10 |
| 2007 | Number of days | 283 | 294 | 283 | 283 |
|      | date          | 10–10     | 10–10    | 10–10   | 10–10   |
| 2009 | Number of days | 290 | 293 | 291 | 290 | 292 | 0 |
|      | date          | 17–10     | 10–10    | 10–10   | 17–10   | 19–10   | 31–12 |
| 2011 | Number of days | 280 | 281 | 281 | 281 | 281 | 285 | 285 |
|      | date          | 8–10      | 8–10     | 9–10    | 8–10    | 12–10   | 12–10 |
| 2013 | Number of days | 295 | 290 | 289 | 291 | 289 | 291 |
|      | date          | 17–10     | 16–10    | 18–10   | 18–10   | 16–10   | 18–10 |
| 2014 | Number of days | 273 | 278 | 273 | 277 | 278 |
|      | date          | 30–09     | 30–09    | 4–10    | 5–10    | 4–10    |
| 2015 | Number of days | 277 | 299 | 299 | 299 | 297 | 277 |
|      | date          | 4–10      | 26–10    | 26–10   | 26–10   | 24–10   | 4–10 |
| 2016 | Number of days | 285 | 282 | 281 | 301 | 284 | 282 |
|      | date          | 9–10      | 8–10     | 28–10   | 12–10   | 11–10   | 9–10 |

| Year | Specification | Białowieża | Legionowo | Pułtusk | Siedlce | Szepietowo | Warsaw | Terespol |
|------|---------------|------------|-----------|---------|---------|------------|--------|---------|
| 2001 | Number of days | 99 | 94 | 94 | 94 |
|      | date          | 9–04      | 4–04     | 7–04    | 4–04    |
| 2002 | Number of days | 100 | 100 | 100 | 100 |
|      | date          | 10–04     | 10–04    | 10–04   | 10–04   |
| 2003 | Number of days | 95 | 93 | 93 | 94 |
|      | date          | 4–04      | 2–04     | 2–04    | 3–04    |
| 2005 | Number of days | 112 | 92 | 114 | 114 | 112 |
|      | date          | 22–04     | 24–04    | 24–04   | 22–04   |
| 2006 | Number of days | 98 | 97 | 97 | 97 |
|      | date          | 8–04      | 7–04     | 7–04    | 7–04    |
| 2007 | Number of days | 113 | 122 | 97 | 95 |
|      | date          | 23–04     | 2–05     | 7–04    | 5–04    |
| 2012 | Number of days | 101 | 100 | 100 | 100 | 101 |
|      | date          | 10–04     | 9–04     | 10–04   | 9–04    |
| 2013 | Number of days | 99 | 98 | 98 | 98 |
|      | date          | 9–04      | 8–04     | 8–04    | 8–04    |
| 2014 | Number of days | 95 | 92 | 92 | 92 |
|      | date          | 5–04      | 2–04     | 2–04    | 2–04    |
| 2017 | Number of days | 111 | 107 | 107 | 107 | 107 |
|      | date          | 21–04     | 17–04    | 17–04   | 17–04   |

| Year | Specification | Białowieża | Legionowo | Pułtusk | Siedlce | Szepietowo | Warsaw | Terespol |
|------|---------------|------------|-----------|---------|---------|------------|--------|---------|
| 2001 | Number of days | 99 | 94 | 94 |
|      | date          | 9–04      | 4–04     | 7–04    |
| 2002 | Number of days | 100 | 100 | 100 |
|      | date          | 10–04     | 10–04    | 10–04   |
| 2003 | Number of days | 95 | 93 | 93 |
|      | date          | 4–04      | 2–04     | 2–04    |
| 2005 | Number of days | 112 | 92 | 114 |
|      | date          | 22–04     | 24–04    | 24–04   |
| 2006 | Number of days | 98 | 97 | 97 |
|      | date          | 8–04      | 7–04     | 7–04    |
| 2007 | Number of days | 113 | 122 | 97 |
|      | date          | 23–04     | 2–05     | 7–04    |
| 2012 | Number of days | 101 | 100 | 100 |
|      | date          | 10–04     | 9–04     | 10–04   |
| 2013 | Number of days | 99 | 98 | 98 |
|      | date          | 9–04      | 8–04     | 8–04    |
| 2014 | Number of days | 95 | 92 | 92 |
|      | date          | 5–04      | 2–04     | 2–04    |
| 2017 | Number of days | 111 | 107 | 107 |
|      | date          | 21–04     | 17–04    | 17–04   |
Table 6. Number of days, starting with the beginning of the year, with the first severe autumn frosts and dates of these events

| Year | Specification | Białowieża | Legionowo | Pułtusk | Siedlce | Szepietowo | Warsaw | Terespol |
|------|---------------|------------|-----------|---------|---------|------------|--------|---------|
| 2001 | Number of days | 269        | 298       | 298     | 297     | 25–10      | 25–10  | 24–10   |
|      | date           | 26–09      |           |         |         | 10–10      |        |         |
| 2002 | Number of days | 283        | 298       | 293     | 292     | 284        | 283    |         |
|      | date           | 10–10      | 11–10     | 10–10   | 11–10   | 10–10      |        |         |
| 2003 | Number of days | 292        | 290       | 290     | 292     | 290        | 292    |         |
|      | date           | 19–10      | 17–10     | 17–10   | 19–10   | 17–10      |        |         |
| 2004 | Number of days | 288        | 288       | 287     | 286     | 14–10      | 12–10  |         |
|      | date           | 14–10      | 12–10     | 14–10   | 13–10   | 14–10      |        |         |
| 2005 | Number of days | 298        | 302       | 301     | 301     | 302        | 298    |         |
|      | date           | 25–10      | 29–10     | 20–10   | 28–10   | 29–10      |        |         |
| 2007 | Number of days | 283        | 294       | 283     | 283     | 283        | 283    |         |
|      | date           | 10–10      | 21–10     | 10–10   | 10–10   | 10–10      |        |         |
| 2009 | Number of days | 290        | 293       | 291     | 283     | 290        | 292    |         |
|      | date           | 17–10      | 20–10     | 18–10   | 10–10   | 17–10      |        |         |
| 2010 | Number of days | 280        | 281       | 282     | 281     | 285        | 285    |         |
|      | date           | 7–10       | 8–10      | 8–10    | 9–10    | 8–10       |        |         |
| 2011 | Number of days | 295        | 290       | 289     | 291     | 289        | 291    |         |
|      | date           | 22–10      | 17–10     | 16–10   | 22–10   | 18–10      |        |         |
| 2013 | Number of days | 273        | 278       | 273     | 277     | 278        | 277    |         |
|      | date           | 30–09      | 5–10      | 30–09   | 4–10    | 5–10       |        |         |
| 2014 | Number of days | 277        | 299       | 299     | 299     | 297        | 277    |         |
|      | date           | 4–10       | 26–10     | 26–10   | 26–10   | 24–10      |        |         |
| 2015 | Number of days | 285        | 282       | 281     | 301     | 285        | 282    |         |
|      | date           | 12–10      | 9–10      | 8–10    | 28–10   | 12–10      |        |         |
| 2016 | Number of days | 291        | 288       | 288     | 288     | 288        | 288    |         |
|      | date           | 17–10      | 14–10     | 14–10   | 14–10   | 14–10      |        |         |

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