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Agroclimatic Zoning of Temperature Limitations for Growth of Stubble Cover Crops

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Abstract: The realization of the expected benefits of stubble cover crops (CCs) depends on sufficient plant growth, which is influenced by the sum of effective temperatures (SET) before the onset of winter and the occurrence of the first early autumn frost (FRST). The objective of this study was to calculate the SET for three dates of CC sowing, August 20 (A), September 6 (B), and September 20 (C), from 1961 to 2020, based on daily data from 268 meteorological stations in the Czech Republic (CR). The dates of FRST, when the daily average and minimum temperatures at 2 m and the minimum temperature at the ground level fell below 0 °C, −3, and −5 °C during CC growth, were recorded. The analysis showed a significant trend in the average SET, which increased by 1.60, 0.87, and 0.97 °C per year for scenarios A, B, and C, respectively. As a result, the area where SET conditions allowed for CC flowering from autumn sowing expanded, as visualized in the agroclimatic maps of the country. The average dates of the FRST shifted by 0.05–0.11 days per year over the sixty years, but this was not significant due to high inter-annual variability. The SET was closely related to the average annual temperature and station elevation (r = |0.95|–|0.99|), while the corresponding trend relationships were weaker (r = |0.40|–|0.43|). This study provides data on the zonation of the conditions required to achieve specific CC management objectives.

Keywords: sum of effective temperatures; development rate; flowering; frost risk; crop damage; mustard; phacelia; buckwheat

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Academic Editor: Nektarios Kourgialas

Received: 25 November 2024
Revised: 23 December 2024
Accepted: 31 December 2024
Published: 9 January 2025

Citation: Haberle, J.; Chuchma, F.; Raimanova, I.; Wollnerova, J. Agroclimatic Zoning of Temperature Limitations for Growth of Stubble Cover Crops. *Climate* **2025**, *13*, 15. https://doi.org/10.3390/cli13010015

1. Introduction

The cultivation of cover crops (CCs), also called catch crops for their importance in retaining nitrogen and other nutrients, represents a well-established farming practice. Several benefits are expected from the cultivation of stubble CCs, which are sown after the harvest of the main crop [1,2]. These benefits include reductions of erosion and the leaching of nutrients, the input of organic matter, as well as the amelioration of compacted soils. The benefits of increased biodiversity, phytosanitary aspects (nematocidal and fungicidal activities), and the suppression of weeds and volunteer plants from the main crop are gaining importance due to demands for reducing the use of agrochemicals [3,4]. Extensive meta-analyses of the impact of CCs on yields of the following primary crops [5,6] have shown reductions of 4 and 8% on average. Still, the introduction of legumes plays a significant role (yield increase of up to 13%) according to these authors. Cover crops could mitigate net greenhouse gas balances by 2.06 ± 2.10 Mg CO_2-eq ha^{-1} yr^{-1} [5], which may be another argument for their wider use. Incorporating CCs into cropping systems is encouraged by government subsidies to achieve compliance with the relevant requirements of the Common Agriculture Policy to mitigate the environmental impacts of intensive agriculture [7–9]. In the Czech Republic (CR), CC cultivation is supported within a regime of direct payments to farmers and funds for agroenvironmental and agroclimatic measures [10–12].

Farmers have specific demands for CCs: they expect benefits and want to avoid possible agrotechnical problems. For example, a longer growth period for CCs has its benefits (flowering, the accumulation of nitrogen in the biomass, a greater root system, the input of carbon into the soil, and bio-drilling effects). However, it may be connected with excessive depletion of soil moisture and nutrients [13], untimely mineralization of N from residues, complications with soil tillage when preparing the seed bed for the following crops, or the "green bridge" effect [14–17].

Attaining the benefits of CCs and avoiding the occurrence of problems depend on satisfactory CC establishment, as well as optimal growth and development. A CC's performance is mostly determined by weather patterns, which are related to the date of sowing and interactions with available water and nutrient supplies in the soil [18–20]. The rate of development of plants is primarily determined by the sum of effective temperatures (SET) above a given threshold (the base temperature (Tb)) and the length of the day [18,21–23]. SET is a commonly used method for estimating important developmental stages, but data on autumn CCs are rare or come from CCs that are grown as main crops in spring and summer [24–26].

One of the important factors limiting the growth of CCs in the temperate zone autumn is frost [27–30]. Even a short drop in temperature (hoar frost) can kill or badly harm sensitive CC species and prohibit their further growth. For example, even a temperature slightly under zero degrees can irreversibly harm buckwheat plants, while the less sensitive mustard or phacelia plants (the most cultivated CCs in the CR) are only damaged by lower temperatures. On the other hand, the natural termination of CC growth may be seen as beneficial by farmers, as it eliminates some of the disadvantages associated with "excessive" biomass production [31,32].

The specific management of CCs must consider the soil–climatic conditions of a site. An effective tool for farmers is agroecological and agroclimatic zoning/regionalization, which considers the effects of various factors on crops in a concise manner, often presented in the form of maps. Zoning provides a framework for the selection of crop species or cultivars and specific agronomy measures based on the distribution of levels of key factors in the region [33,34]. Soil and agroclimatic zoning methods are also widely used for administrative purposes, especially for stipulating recommendations or restrictions on the use of farming fertilizers and agroecological measures in accordance with the Codes of Good Agricultural Practice, Nitrate Directive, and various agroecological regulations [12,35–37]. Agroclimatic zoning in the temperate zone has focused on the main crop-growing season [38,39], while the autumn season, which is important for stubble catch crops, has attracted less attention [25,40].

Therefore, we analyzed the SET and FRST during autumn for model representatives of CCs: white mustard, phacelia, and buckwheat. Their fast transition to the generative stage and different sensitivities to frost provide a framework for an agroclimatic analysis that is relevant to farming practices. Mustard and phacelia are by far the most widely grown CC species in the Czech Republic; common buckwheat, along with field pea, vetch, clover, oats, ryegrass, niger, or fodder radish, are grown on a smaller area, most often in mixtures.

Our study addressed the following questions: (1) whether SETs determined in common CC sowing dates while respecting the administratively specified minimum growth period and the earliest harvest end date have changed significantly in the CR (Figure 1) during

1961–2020, and (2) whether the occurrence of the first frost days at ground level and at a height of 2 m has changed significantly over these 60 years in the CR.

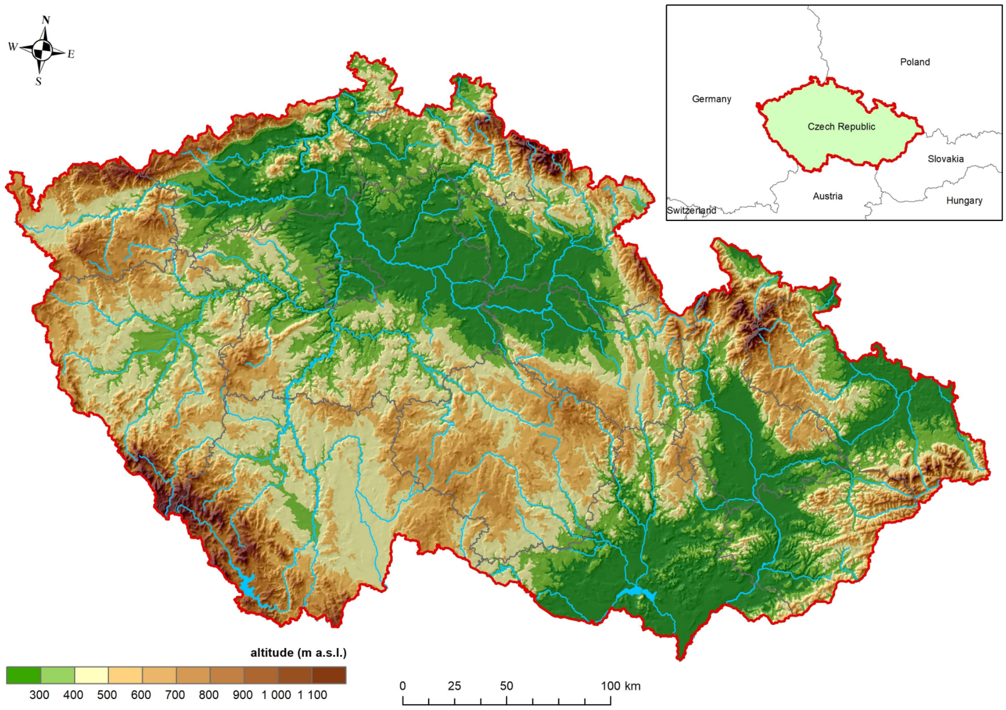

Figure 1. Location and topography of the Czech Republic.

It can be expected that the main manifestation of climate change, increasing temperatures, should also affect the agroclimatic conditions for the growth and development of CC [8,21,37]. This led to the working hypotheses of this study. We assumed that the SET for a given period of CC growth has increased over the past sixty years. As a result, CCs sown on specific dates would grow under conditions that allow them to reach flowering on an earlier date and in more parts of the CR. We expected that the occurrence of the FRST has shifted towards winter during the study period and that the SET and FRST are correlated with the average daily temperature and the altitude of a site.

2. Materials and Methods

2.1. Methodical Approach

An analysis of the sum of effective temperatures (SETs) required for the flowering phase to begin was performed. The average indicative SETs for the flowering of the frost-sensitive common buckwheat (*Fagopyrum esculentum* Moench), medium-tolerant phacelia (*Phacelia tanacetifolia*), and white mustard (*Sinapis alba* L.) were compared with the calculated SETs.

The flowering stage was selected as an important stage, as it has benefits for invertebrates, involves changes in biomass quality, and has a sensitivity to frost. Data on the sum of temperatures required to reach the flowering stage were based on unpublished observations in field experiments and farms in the CR, as the data from the literature are scarce [23,26]. The possible effects of the length of the day, available N, and water supply on the rate of development were not considered.

The SET (Tbase > 0 °C; positive temperatures were summed) ranges for the start of the flowering stage, based on field observations, were 420–500 °C, 490–605 °C, and 595–720 °C for buckwheat, mustard, and phacelia, respectively, and were affected by local factors.

We used 450, 550, and 650 °C as the indicative reference SETs to relate the results of the agroclimatic analysis to the conditions required for the start of flowering.

Three scenarios (A to C) with different dates of sowing and minimum durations of growth of the CCs were used; the combination of the start and duration of growth were set according to legal requirements for agroenvironmental climate measures under the Cross-Compliance and whole-farm eco-payments [10,11]. These requirements ensure a minimum duration of CC growth (from the time of sowing) of 8 weeks, until at least October 30, after which the CCs can be terminated to establish winter crops (Table 1).

Table 1. Set of conditions for cover crop growth used for the calculation of the sums of effective temperatures.

Scenario		Sowing	Termination	Duration of Growth and Temperature Summation
A	The common date of sowing on farms and the earliest allowed date of CC termination	August 20	November 1	74 days
B	The sowing date according to the earliest allowed date of CC termination and 8 weeks of growth	September 6	November 1	56 days
C	Delayed sowing date and 8 weeks of growth	September 20	November 15	56 days

2.2. Climate Data

Daily average air temperature data (at a height of 2 m) in 1961–2020 from the Technical Data Series (TDS) were used for the calculation of the sum of effective temperatures (SET) with a base temperature of 0 °C (Tb > 0 °C). The TDS is based on measured data from the network of 268 climatological stations of the Czech Hydrometeorological Institute. The input data were subjected to data quality control using ProClimDB software v.1 [41]. After the errors were corrected, the series was homogenized. Missing daily values were also added for each climatological station using geostatistical methods [42]. Daily average and minimum air temperatures at a height of 2 m and the ground minimum temperature (at 5 cm above the ground) at the same stations were analyzed to determine the day of the year (DOY) of the first occurrence of a temperature below 0 (FRST0), −3 (FRST-3), and −5 °C (FRST-3) from September 1 onwards. TDS data for the ground minimum temperature from 144 stations were available for this study. The annual values of the SET and FRST for the individual stations were calculated. Based on these, statistics for the stations and the whole country were calculated.

Trends in the average SET and FRST during the study period were calculated from annual average data (average of all sites in an individual year). The average values of the SET and the first occurrence of frost days for the first and last decades of the period of 1961–2020 were determined and compared to each other. The average values of SET and FRST for 1961 and 2020 were calculated using regression equations. The average SET (Table A1) and FRST (Table A2) at individual sites over the study period were calculated to examine the relationships between the SET or FRST and the average air temperature or site elevation.

Agroclimatic maps of the spatial distributions of the SET and FRST and maps of linear trends in the SET in 1961–2020 across the territory of the CR were constructed using regression kriging (at a resolution of 500 × 500 m), taking into account the dependence of temperatures on longitude, latitude, altitude, and slope. The resulting raster layers were subsequently processed using the ArcGIS 10.6.1 software environment (ArcGIS Enterprise, Redlands, CA, USA); smoothing was performed using the nearest-neighbor method, and maps were created. For the comparison, maps of the average SET and its trends were created for 1961–1970 and 2011–2020.

2.3. Statistical Analysis

Statistical analysis, including the calculation of linear trends in the SET and FRST, was carried out using ProClimDB software [41]. The statistical significance of the emerging trends was evaluated using *t*-tests at a significance level of 0.05. The relationships between the average SET or FRST and the altitude or average daily temperature of the sites were evaluated using the Pearson correlation coefficient at $p < 0.05$ with Statistica 13 (TIBCO Software Inc., Palo Alto, CA, USA, 2018).

3. Results

3.1. Sum of Effective Temperatures (SET)

The SET data calculated for the three dates of stubble CC sowing (the common dates of sowing with the minimum growth period, eight weeks of growth, and termination after October 30 (Table 1)) are shown in Table 2. The average SETs over the entire sixty-year period reached 825.5, 562.2, and 447.3 °C for scenarios A, B, and C, respectively. The difference between the lowest and highest average SETs in the examined years reached 332.8, 284.6, and 302.7 °C for scenarios A to C (Figure 2). The annual variability (coefficient of variability) in the average SET increased from 8.4% in scenario A to 11.0 and 13.9% in scenarios B and C. Variability increased significantly with altitude (r = 0.88–0.93) and decreased with the average temperature of a site (r = −0.95) (Table 2).

Table 2. Basic statistical parameters of the average SET and correlations among SET, trends, and coefficient of variance (CV) of SET with average annual temperature or altitude of the sites. Statistical parameters were calculated from the average annual values of the sites; correlation coefficients were calculated from the annual averages of individual sites.

Statistical Parameter or Correlation	Unit	Scenario/Date of Sowing A/August 20	B/September 6	C/September 20
Average	°C	825.5	562.2	447.3
Minimum value (min)	°C	623.5	406.6	272.2
Maximum value (max)	°C	956.3	691.2	575.0
Difference between max and min	°C	332.8	284.6	302.7
Median	°C	814.5	557.4	450.0
Standard deviation	°C	69.5	61.9	62.3
Coefficient of variance (CV)	%	8.42	11.01	13.94
Skew	-	−0.19	−0.07	−0.27
Kurtosis	-	−0.31	−0.49	−0.04
Lower quartile (25%)	°C	765.0	515.9	414.8
Upper quartile (75%)	°C	886.8	612.3	488.2
Linear trend	°C per year	1.60	0.87	0.97
p-value of *t*-test	-	0.001	0.058	0.036
Average for 1961	°C	778.3	536.5	418.7
Average for 2020	°C	872.8	588.0	475.9
Correlation				
Average SET and altitude of sites	-	−0.95	−0.95	−0.95
Average SET and average annual temperature	-	0.99	0.99	0.98
Trends in average SET and altitude	-	−0.42	−0.43	−0.43
Trends in average SET and annual temperature	-	0.40	0.41	0.40
CV of SET and altitude	-	0.88	0.93	0.92
CV of SET and average annual temperature	-	−0.90	−0.95	−0.95

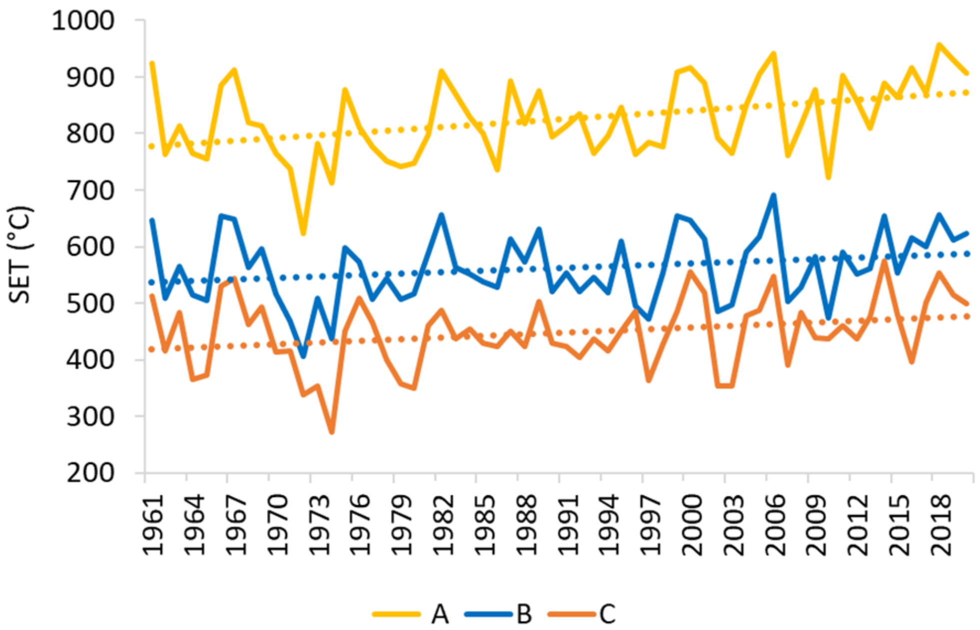

Figure 2. Variability in the average SETs across the three scenarios, with sowing on August 20 (A), September 6 (B), and September 20 (C) during 1961–2020 in the Czech Republic.

The minimum and maximum SETs at individual sites over the sixty years ranged from 409 to 1020, 259 to 707, and 186 to 583 °C in scenarios A to C; the variability (CV) in the average SET over the sixty years at individual sites was 11.5, 12.3, and 14.7% in scenarios A, B, and C (Table A1).

The average SET increased by 1.60, 0.87, and 0.97 °C per year in scenarios A, B, and C, respectively, between 1961 and 2020 (Table 2). The trend (calculated from average annual values) was significant for scenarios A and C ($p > 0.036$) and marginally insignificant for scenario B ($p < 0.058$). These trends represent increases of 118.5, 48.9, and 54.3 °C between 1961 and 2020 in the respective scenarios, which represent 8.4–26.3% of the SET needed to start flowering in the three CCs. The average trend in SET at individual sites across the territory of the CR varied, with a significantly negative relationship with the altitude of a site (r from −0.42 to −0.43) and a significantly positive one with the average temperature (r = 0.40–0.41). The annual trends in SET for individual sites were significant at 87.7, 44.8, and 53.7% of the sites in scenarios A, B, and C, respectively.

In scenario A, the SET reached 650 °C and higher, owing to an earlier start and longer duration of summation (Table 1), for virtually the whole country (99%) at the start (1961–1970) and end of the examined period (2011–2020). In scenario B, the area where the SET was greater than 550 °C and 650 °C decreased strongly compared to scenario A, but it also increased by 13 and 19% in 2011–2020 compared to 1961–1970. In scenario C, over 59% and 81% of the country still reached a SET over 450 °C in each respective decade, but only 14% reached an SET of 550 °C in 2011–2020, and virtually none attained an SET of 650 °C (Figure 3, Table A3).

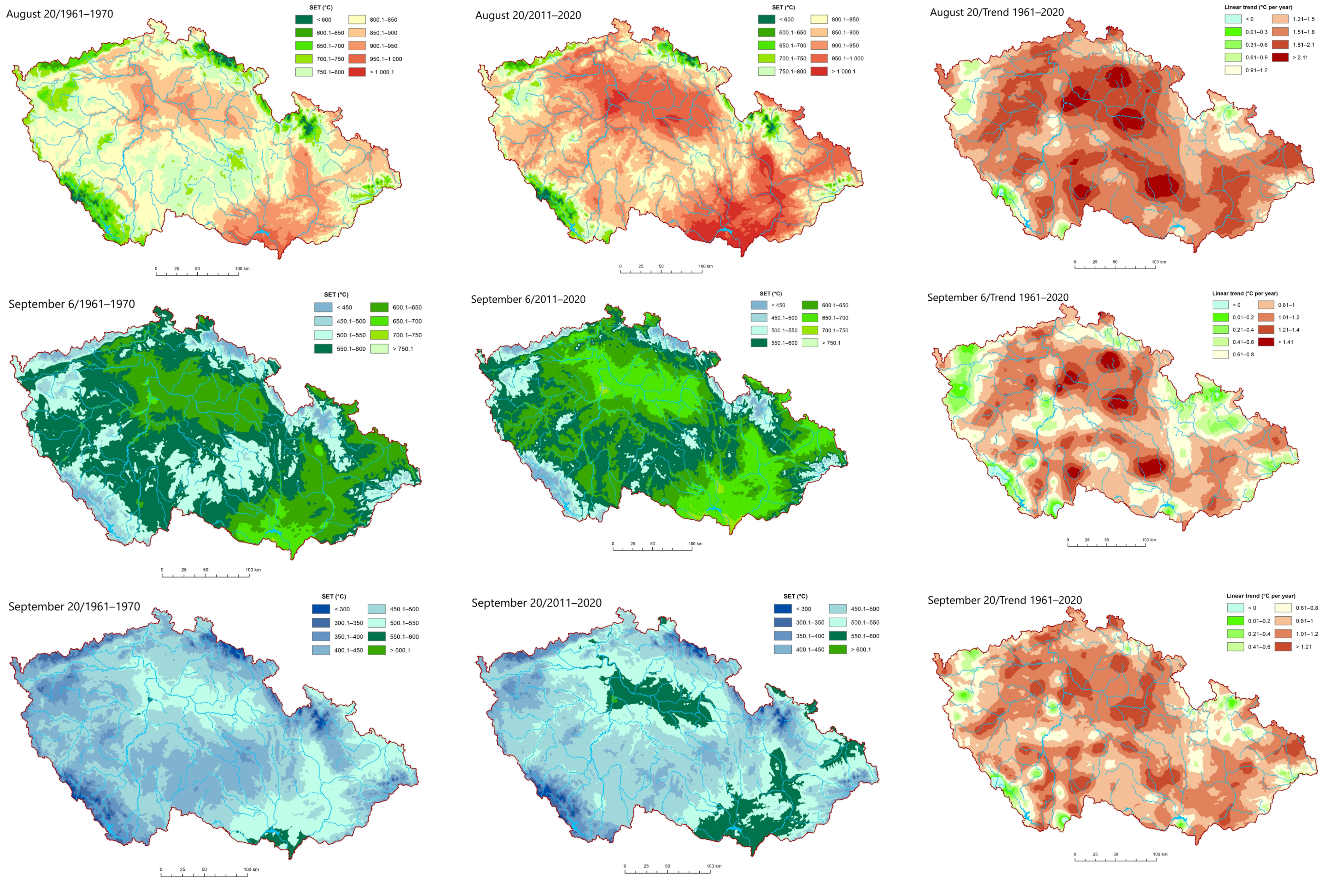

Figure 3. Agroclimatic maps of the average SETs for 1961–1970 and 2011–2020 and trends in the average SET in the Czech Republic during 1961–2020 for sowing August 20, September 6, and September 20.

3.2. Date of the First Autumn Frost (FRST)

On average, over the study period, the first occurrences of minimum ground temperatures under 0 (FRST0), −3 (FRST-3), and −5 °C (FRST-5) were on DOY 266 (September 23), 290 (October 17), and 303 (October 30), respectively. The DOYs when the average (316, 334, and 341) and minimum (287, 309, and 324) air temperatures at 2 m reached frost levels were 19–50 days later than those at ground level (Table 3).

Table 3. Basic statistical parameters of the day of the year (DOY) for the first occurrence of temperatures below 0 (FRST0), −3 (FRST-3), and −5 °C (FRST-3) and the correlation between the FRST and the average annual temperature and altitude of the sites. The statistical parameters were calculated from the average annual values of the sites. The correlation coefficients were calculated from the annual average values of the respective FRSTs for individual sites. The average values for 1961 and 2020 were calculated from linear trends.

Statistical Parameter Or Correlation	Unit	Average at 2 m FRST0	FRST-3	FRST-5	Minimum at 2 m FRST0	FRST-3	FRST-5	Minimum at Ground Level FRST0	FRST-3	FRST-5
Average	DOY	316	334	341	287	309	324	266	290	303
Difference compared to FRST0	Days		18	25		22	37		24	37
Difference compared to Average at 2 m	Days				29.3	25.0	17.1	50.2	44.1	37.6
Difference compared to Minimum at 2 m	Days							20.9	19.1	20.5
Minimum value (min)	DOY	296	311	319	268	288	296	247	272	285
Maximum value (max)	DOY	344	355	360	307	338	351	288	309	330
Difference between max and min	Days	48	44	41	38	49	55	41	36	44
Median	DOY	317	333	341	286	310	324	266	289	304

Table 3. *Cont.*

Statistical Parameter Or Correlation	Unit	Average at 2 m FRST0	FRST-3	FRST-5	Minimum at 2 m FRST0	FRST-3	FRST-5	Minimum at Ground Level FRST0	FRST-3	FRST-5
Standard deviation	Days	9.4	11.0	10.8	8.9	11.4	12.1	9.2	9.8	10.6
Coefficient of variance	%	327	349	356	299	323	340	278	306	317
Lower quartile (25%)	DOY	310	327	333	281	301	316	261	283	296
Upper quartile (75%)	DOY	322	342	349	293	316	332	272	297	308
Linear trend	Days per year	0.05	0.11	0.10	0.09	0.10	0.10	0.10	0.06	0.07
p-value of *t*-test	-	0.44	0.18	0.22	0.20	0.24	0.29	0.17	0.40	0.42
Average for 1961	DOY	315	331	338	284	306	321	263	288	301
Average for 2020	DOY	318	337	344	289	312	327	269	292	305
Correlation										
FRST and average annual temperature	-	−0.95	−0.96	−0.92	−0.63	−0.63	−0.72	−0.55	−0.45	−0.39
FRST and altitude	-	0.97	0.96	0.92	0.71	0.70	0.79	0.64	0.54	0.49

The average DOY of the first frost varied greatly during the study period (Table 3, Figure 4). The dates of the FRST in the study period differed, at most, by 41–48 (average at 2 m), 38–55 (minimum at 2 m), and 36–44 (minimum at ground level) days. The average date of the FRST at individual stations/sites differed by 40–70 days due to dependence on altitude. The differences were larger for FRST0 compared to FRST-3 and FRST-5 (Table A2).

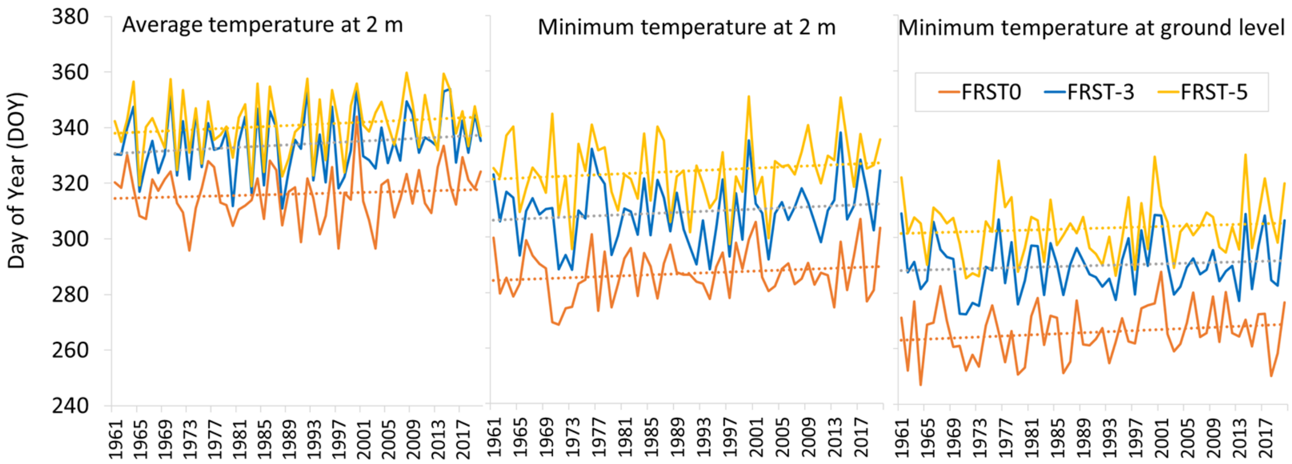

Figure 4. Variability in the average day of the first occurrence of temperatures under 0, −3, and −5 °C (FRST0, FRST-3, and FRST-5, respectively) during 1961–2020 in the Czech Republic.

The shifts in FRST0, FRST-3, and FRST-5 were similar at 2 m and ground level and ranged between 0.05 and 0.11 days/year, which represents an average shift of 3.2–5.8 days towards winter during sixty years. The trends were not significant at $p < 0.05$ due to high year-to-year variability (Table 3). The sixty-year trends calculated for individual sites were significant in 8, 15, and 20% of cases for the 2 m average, 2 m minimum, and ground temperatures, without a clear relationship to altitude or average temperature.

Significant relationships were found between the average FRST0, FRST-3, and FRST-5 and the altitude or average annual air temperature of a site. The correlation coefficients were stronger for the average (r = l |0.92|–|0.97|) and minimum (r = |0.63|–|0.79|) temperatures at a height of 2 m than for the ground temperature (r = |0.39|–|0.64|) (Table 3). The dependence of FRST on the average air temperature and altitude is documented in the agroclimatic maps (Figure 5).

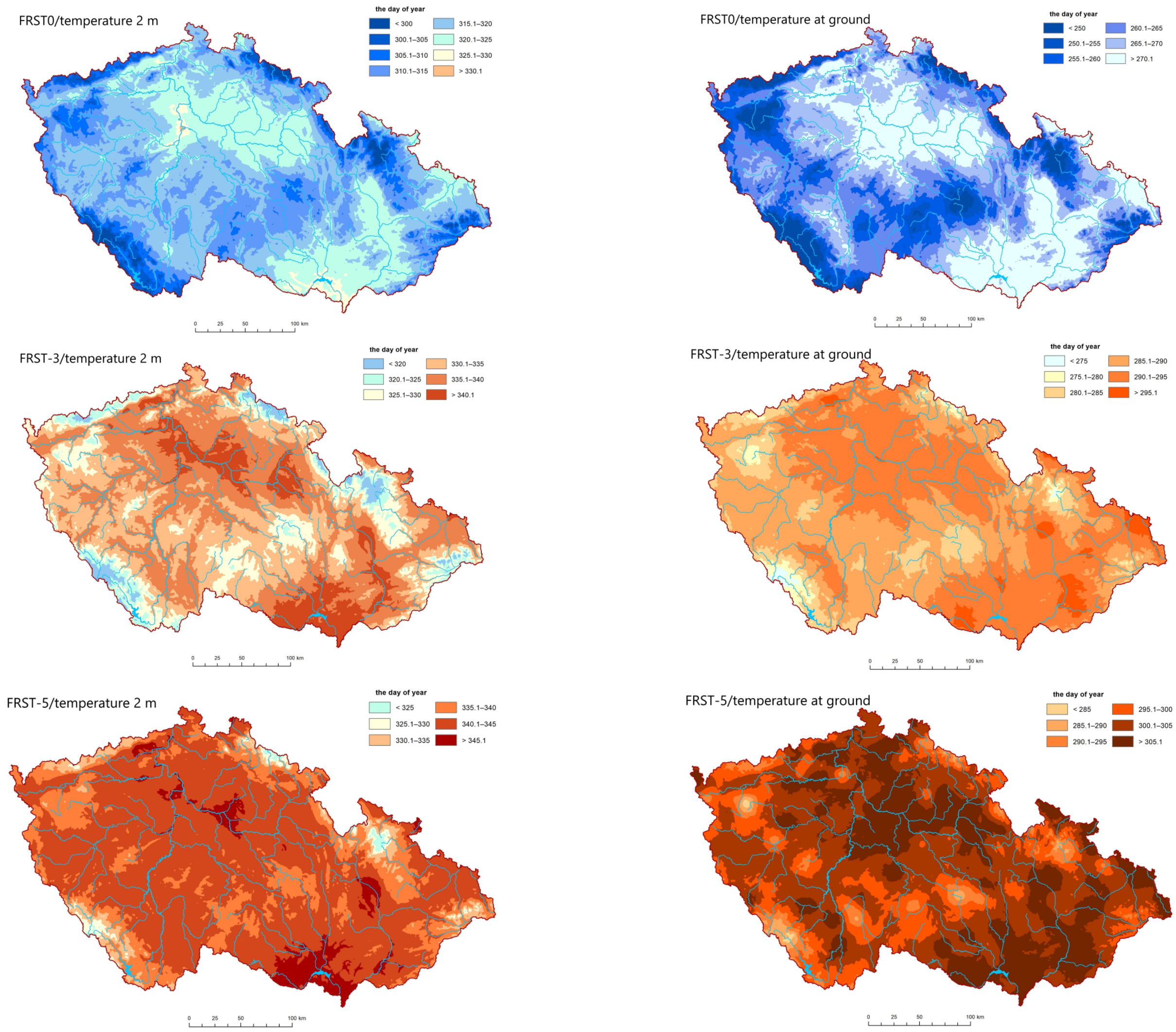

Figure 5. Agroclimatic maps of the average first day of the year (DOY) with temperatures at 2 m and at ground level under 0, −3, and −5 °C (FRST0, FRST-3, and FRST-5, respectively) in the Czech Republic during 1961–2020.

4. Discussion

In this study, the main climatic factors (temperature sums and early frost occurrence) limiting the growth and development of representative CCs with different sensitivities to low temperatures (white mustard, phacelia, and buckwheat) in autumn were analyzed.

4.1. Sum of Effective Temperatures (SETs)

As expected, the sowing date was an important factor in determining the SET, which is related to the decreasing air temperature during autumn [19,43]. For example, according to Teixeira et al. (2016), sowing dates contribute more to the total variability in the effectiveness of CCs than weather does [44]. It should be stressed that radiation also decreases as the year progresses, and its interception by CCs depends on the duration of sunshine and other factors [20,45].

Our analysis confirmed our working hypothesis that the SET increased during the examined period of 1961–2020. This is in agreement with national and global data that show increasing temperatures, especially in the last thirty years [46–48]. Agroclimatic studies often document a gradual rise in temperatures for the whole year or main growing season. Our analysis also showed an increasing trend for the late summer and autumn growing seasons of CCs. Mozny et al. (2023) confirmed a significant increase in the average annual air temperature in the CR of 0.04 °C $year^{-1}$, i.e., 1.5 °C in total, for 1961–2020; the trend in the SET (Tb > 5 °C) was 6.62 °C per year during the vegetation period (April–September, i.e., 183 days) or 2.03 °C per year when calculated for only 56 days [39]. Our data showed that the average trend in the SET was 1.60, 0.87, and 0.97 °C per year during the growth of the CCs (73 and 56 days) in 1961–2020 (calculated with Tb > 0 °C). However, the trend was not significant for some stations, which warrants further analysis.

Warmer weather accelerates the development and harvesting of main crops [49,50], allowing for earlier sowing and a longer growth duration for CCs [18,24,37]. This is especially important at higher elevations and in climate regions with short growing seasons [51]. Further, faster growth may eliminate some of the negative impacts of delayed sowing of CCs, such as less depletion of residual nitrates [17,18,20]. The observed trends in the SET represent average increases of 48.9 and 54.3 °C (B and C) between 1961 and 2020, i.e., 10.9 and 12.1% of the SET needed for buckwheat flowering to start. As visualized in the maps (Figure 3), the area where the SET reached the level required for the flowering stage expanded over the years (for the same sowing date) to higher altitudes. At the same time, the shift in crop cultivation to higher regions with less risk of droughts is in progress [38,47].

The prolonged growth duration and enhanced development have several benefits, such as enhanced attractiveness for insects, the suppression of weeds, and improved soil environments, but may also bring unwanted consequences [52,53]. The expectations of farmers may even be contradictory. On the one hand, in the generative stage, the quality of biomass residues changes significantly, and the C:N ratio widens (contributing to slower decomposition). Their processing during tillage may become complicated, and the plants may deplete the soil moisture reserves in the root zone [14,32,54]. On the other hand, longer growth ensures greater demand and a large root system for nitrate depletion in the topsoil and subsoil, and it has bio-drilling effects [16,17,55,56]. However, it should be noted that faster development does not automatically mean a higher biomass; growth also depends on the sufficient availability of water and nutrients.

4.2. Date of the First Autumn Frost (FRST)

The analysis showed that the first occurrence of a temperature under 0, −3, and −5 °C shifted by 0.05–0.11 days per year during the study period. However, the changes were not significant due to the high year-to-year variability. Therefore, the working hypothesis regarding the expected shift of the FRST towards winter was rejected. In addition, at most sites, the FRST did not show any significant trends. Similarly, Mozny et al. (2023) found only a slight decrease in the probability of frost during the main growing season in the CR in 1961–2020. The average "delay" of the first frost, calculated from the trends, was only 3–6 days in 2020 compared to 1961, while year-to-year differences in the occurrence of frost reached tens of days (Table 3). Frost at ground level occurred, on average, on DOY 266 (September 23), 290 (October 17), and 303 (October 30), which was before the earliest allowed date for the forced termination of CC growth (November 1), and 19–50 days sooner than the FRST at a height of 2 m. The risk of plant destruction due to low temperatures is relevant, especially for the most sensitive CCs, such as buckwheat, sorghum, and hemp. Due to the increasing SET and faster development, the plants have a greater chance of reaching the flowering stage before the first frost occurs.

The ground temperature and its impact are influenced by the specific site and its microclimatic factors, the microtopography of the field, the plant's physiological status, and the soil cover (bare soil versus crop canopy). The drop in minimum air temperatures at a height of 2 m to under −3 and −5 °C (which occurred, on average, at the start of November) may better indicate the risk of serious harm to important moderately cold-tolerant CC species, such as phacelia or mustard. This corresponds with observations in our field experiments and on farms.

The natural termination of CC growth may be seen as beneficial by farmers, as it eliminates some of the disadvantages of “excessive” biomass and the need for mechanical or chemical termination of growth; it also reduces the excessive depletion of soil water reserves (for subsequent crops) and forms a mulch layer that reduces evaporation and the amount of biomass during tillage for the subsequent main crop [21,28,31,32]. A gradual frost-induced termination of CCs may provide a small amount of available N compared to the large flush of N after the termination of the entire cover crop biomass in ecological cropping systems [57]. On the other hand, the early mineralization of the CC biomass and untimely N release increase the risk of nitrate leaching [58,59] and nitrous oxide emissions [60]. CC management should consider the effect of faster development on the C/N ratio, which correlates with the rate of N mineralization [17,61–63]. The practical application of this concept [57,64] is complicated by the high annual variability of frost occurrence. Still, the analyzed data provide some guidance regarding the probability of frost; for example, 50% of the ground-level FRST0, FRST-3, and FRST-5 were within time intervals of 11.5, 14.1, and 12.1 days, respectively, during the study period (Table 3).

The relationships between the SET, FRST, and the average annual air temperature or altitude of a site, as visualized in the agroclimatic maps (Figures 3 and 5), suggest that these data can be used for the regionalization of certain agronomic measures. The realization of this application requires reliable prediction of site-specific frost occurrence dates and the sensitivities of different CC species to temperature drops [27]. The development of administrative measures, recommendations, restrictions, and limitations, which are often based on agroclimatic zoning constructed from long-term agroclimatic data, should consider the relatively rapid changes in climate [8,9,18,38]. The increasing temperatures and variable termination of CC growth due to frost may have a significant effect on evapotranspiration, residue mineralization, and nitrogen turnover and losses, which might demand modification of the stipulated measures, such as those from the Nitrate Directive and GAP [37,65].

5. Conclusions

This agroclimatic analysis confirmed the assumption that SET has been increasing in the Czech Republic over the last 60 years. The expected shift in the occurrence of first frosts towards winter was not statistically significant, but the data suggest a certain trend despite the large annual variability. The resulting agroclimatic maps show conditions relevant to CC cultivation and can be used as a broader framework for administrative decision-making and the regionalization of CC groups and some agrotechnical measures. Here, the observed relationships between the agroclimatic conditions and average temperature or site altitude can be well applied. It must be emphasized that agroclimatic analyses use assumptions and simplifications of plant biology, uniformity of plants’ nutritional and physiological statuses [26,30], and microclimatic conditions [66], which are more complex in the real world and demand further field research. In particular, the use of natural termination of plant growth by frost for targeted CC management on farms will require more precise data on species and variety-specific responses, the effect of developmental stage, and the plant’s physiological status (nutrients and water) on CC sensitivity or microclimatic conditions in stands of mixtures of species of different ages.

However, there will still be more or less uncertainty due to weather variability, but this is a common part of many decisions in field crop production. More reliable recommendations to support farmers’ decision-making will require data from trials under diverse soil–climatic conditions and farming systems, and useful insights can also be gained from on-farm CC monitoring.

Author Contributions: Conceptualization, J.H. and F.C.; methodology, F.C. and J.H.; databases and software, F.C.; formal analysis, I.R.; investigation, J.H. and I.R.; resources, J.W.; writing—original draft preparation, J.H.; writing—review and editing, J.H., J.W. and I.R.; visualization, F.C.; supervision, J.W.; project administration, I.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the MINISTRY of AGRICULTURE of the CZECH REPUBLIC, grant numbers QK21010308 and institutional support MZe-RO0423.

Data Availability Statement: Daily climate data from the meteorological stations in the Czech Republic for previous decades can be downloaded from the Czech Hydrometeorological Institute's site (https://www.chmi.cz/historicka-data/pocasi/denni-data/Denni-data-dle-z.-123-1998-Sb; accessed on 3 January 2025).

Conflicts of Interest: The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Appendix A

Table A1. Selected statistical parameters of SET. Statistical parameters were calculated from SET data for individual sites and averaged over the study period.

Statistical Parameters	Unit	Scenario/Term of Sowing A/August 20	B/September 6	C/September 20
Average	°C	825.5	562.2	447.3
Minimal value (min)	°C	408.8	259.4	185.8
Maximal value (max)	°C	1019.5	706.9	583.4
Difference max-min values	°C	610.7	447.5	397.7
Median	°C	819.6	559.9	449.3
Standard deviation	°C	94.9	69.2	63.9
Coefficient of variance	%	11.50	12.31	14.27
Skew	-	−0.14	−0.05	−0.23
Kurtosis	-	−0.22	−0.41	0.00
Lower quartile (25%)	°C	770.9	513.4	406.5
Upper quartile (75%)	°C	885.8	612.3	492.5

Table A2. Selected statistical parameters of FRST. Statistical parameters were calculated from FRST data for individual sites and averaged over the study period.

Statistical Parameters	Unit	Average 2 m FRST0	FRST-3	FRST-5	Minimal 2 m FRST0	FRST-3	FRST-5	Minimal Ground FRST0	FRST-3	FRST-5
Average	°C	316	334	341	287	309	324	266	290	303
Minimal value (min)	°C	273	295	307	243	280	297	216	261	279
Maximal value (max)	°C	335	343	346	311	335	342	286	310	324
Difference max-min	°C	61	49	40	68	54	45	70	49	46
Median	°C	318	336	342	288	309	325	270	291	304
Standard deviation	°C	20.63	21.51	21.30	18.93	20.07	20.83	25.76	25.17	26.34
Coefficient of variance	%	6.52	6.44	6.25	6.60	6.49	6.43	9.69	8.68	8.68
Skew	-	−1.98	−2.01	−3.22	−1.62	−0.42	−0.99	−1.41	−0.64	−0.25
Kurtosis	-	6.97	5.79	13.72	7.01	1.77	1.93	2.45	1.25	0.20
Lower quartile (25%)	°C	314	331	341	284	305	321	261	285	298
Upper quartile (75%)	°C	321	339	343	291	314	328	275	295	309

Table A3. Spatial distribution of the average SET, calculated from maps with a resolution of 500 × 500 m per pixel, for scenarios A to C in the territory of the Czech Republic in 1961–1970 and 2011–2020.

SET °C	No. of Pixels (500 × 500 m) 1961–1970	2011–2020	% of CR Territory 1961–1970	2011–2020
Scenario A				
<450	43	2	0.01	0.00
>450	315,741	315,782	99.99	100.00
<550	748	521	0.24	0.16
>550	315,036	315,263	99.76	99.84
<650	6760	4215	2.14	1.33
>650	309,024	311,569	97.86	98.67
Scenario B				
<450	7109	6624	2.25	2.10
>450	308,675	309,160	97.75	97.90
<550	88,430	46,434	28.00	14.70
>550	227,354	269,350	72.00	85.30
<650	305,306	244,322	96.68	77.37
>650	10,478	71,462	3.32	22.63
Scenario C				
<450	128,243	60,080	40.61	19.03
>450	187,541	255,704	59.39	80.97
<550	312,573	270,732	98.98	85.73
>550	3211	45,052	1.02	14.27
<650	315,784	315,784	100.00	100.00
>650	0	0	0.00	0.00

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