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Original Article

Spatial and Temporal Variations of Frost-Free Seasons in the Meriç-Ergene Basin

Ebru Elif Arslantaş Civelekoğlu[1] , Umut Mucan[2]✉

[1] Aydın Adnan Menderes University, Faculty of Agriculture, Department of Biosistems Engineering, Aydın, TÜRKİYE,
[2] Çanakkale Onsekiz Mart University, Faculty of Agriculture, Department of Farm Structures and Irrigation, Çanakkale, TÜRKİYE

[1] https://orcid.org/0000-0003-4217-9179, [2] https://orcid.org/0000-0002-7126-9774

✉: umut.mucan@comu.edu.tr

ABSTRACT

Long-term climate observations reveal a significant upward trend in global average temperatures in recent years. This has led to changes in the timing of frost events throughout the year. Understanding changes in frost-free season length is essential for adapting agricultural production to climatic conditions and minimizing frost-related damage. This study examined the spatial and temporal changes in the parameters of first frost day in autumn (FFA), last frost day in spring (LFS), and frost-free season (FFS) using daily minimum temperature data recorded in the Meriç-Ergene Basin from 1980 to 2024. Spatial distributions were mapped using the inverse distance weighted (IDW) method. Temporal trends were evaluated using the Mann–Kendall test and trend magnitudes were calculated using Sen's slope method. The findings reveal that the average frost-free season in the region lasts approximately 7.6 months. Long-term trend analysis revealed that while LFS shifted backward by approximately 1.6 days per decade, FFA advanced by approximately 5.5 days per decade. Consequently, the frost-free season lengthened by approximately 7.4 days per decade, primarily due to the delayed FFA.

Key words: Meriç-Ergene Basin, Climate Change, Frost, Mann-Kendall Test, Sen's Slope Estimator

Meriç-Ergene Havzasında Don Olmayan Dönemlerinin Mekansal ve Zamansal Değişimleri

ÖZ

Uzun yıllar iklim verileri, son yıllarda küresel ortalama sıcaklıklarda önemli bir artış eğilimi olduğunu ve bu durumun yıl içinde don olaylarının zamanında değişimlere yol açtığını göstermektedir. Don olmayan dönemlerin süresindeki değişimleri belirlemek, tarımsal üretimin iklim koşullarına uyumunu artırmak ve dona bağlı zararları en aza indirmek açısından kritik öneme sahiptir. Bu çalışmada, Meriç-Ergene Havzası'nda 1980–2024 yılları arasında kaydedilen günlük minimum sıcaklık verileri kullanılarak sonbahar ilk don günü (İDG), ilkbahar son don günü (SDG) ve don olmayan dönem (DOS) parametrelerinin mekânsal ve zamansal değişimleri incelenmiştir. Mekânsal dağılımlar Ters Mesafe Ağırlıklı (IDW) yöntemiyle haritalandırılmış, zamansal eğilimler Mann–Kendall testi ile değerlendirilmiş, eğilimlerin büyüklükleri ise Sen'in eğim yöntemiyle hesaplanmıştır. Bulgular, bölgedeki ortalama don olmayan dönemin yaklaşık 7,6 ay sürdüğünü ortaya koymaktadır. İncelenen dönemde SDG tarihlerinin her on yılda ortalama 1,6 gün erkene kaydığı, İDG tarihlerinin ise yaklaşık 5,5 gün geciktiği belirlenmiştir. Sonuç olarak, don olmayan dönem her on yılda yaklaşık 7,4 gün uzamış ve bu uzamanın temel belirleyicisi İDG tarihindeki gecikme olmuştur.

Anahtar kelimeler: Meriç-Ergene Havzası, İklim değişikliği, Don, Mann-Kendall testi, Sen'in eğim testi.

INTRODUCTION

Temperature plays a critical role in determining plant growth, development, and yield (Luo, 2011). According to current assessments, global surface temperatures have increased by approximately 1.1 °C compared to pre-industrial levels during the period 2011–2020 (IPCC, 2023). However, numerous studies on a global scale since 1950 have proven that the increase in minimum temperatures, which are significantly closely related to frost, is more pronounced than the increase in maximum temperatures (Karl et al., 1993; Easterling et al., 1997; IPCC, 2001; Erlat & Türkeş, 2016; Thorne et al., 2016; Sun et al., 2019).

Changes in the timing of frost events are highly significant for agriculture because plants are extremely sensitive to frost damage) (Wassan et al., 2021). The length of the frost-free season (FFS)—defined as the interval between the last spring frost and the first autumn frost—essentially marks the window in which crops can grow without frost risk. When this window shifts, farmers are forced to adapt their management practices. For example, the choice of planting date, the type of crop variety to be grown, as well as strategies for irrigation or the timing of pesticide and fertilizer use may all need to be reconsidered (Kukal & Irmak, 2018). For instance, a longer FFS due to an earlier last frost date in spring and a delay in the first frost date in autumn enables advancement of crop sowing dates thus leading to extension of the growing season and reduction in risk of frost damage (Li et al., 2022). While prolongation of FFS under climate change conditions initially seems beneficial for crop production, it can lead to adverse consequences. Anomalous temperatures relative to seasonal norms trigger plants to wake up early dormancy and accelerate vegetative growth leading to “false springs” that increase their susceptibility to frost damage. In such cases, frost taking place towards the end of spring can cause serious damage to sensitive tissues such as buds and flowers, particularly in fruit trees (Ault et al., 2013; Zahradníček et al., 2024). Additionally, elevated temperatures can negatively impact crop productivity, especially in high-altitude regions. For example, it has been reported that each additional day in FFS is associated with a reduction in potential spring wheat yield, ranging from 17.4 kg/ha at altitudes below 2000 m to 66.5 kg/ha at altitudes above 4000 m (Zhang & Lu, 2023). The analysis highlights the obtained results that cultivation zones may need to be redefined: warm-climate crops are likely to be expanded, while cool-climate crops may have to be relocated to colder areas (Dorji et al., 2021; Li et al., 2022). In other words, monitoring the temporal and spatial dynamics of frost-free seasons provides valuable, data-driven guidance for climate adaptation and agricultural decision-making.

Türkiye's wide geographical diversity and different climate characteristics create significant regional differences in terms of environmental conditions affecting agricultural productivity (Hultgren et al., 2025). This necessitates detailed analyses at the local scale. Therefore, this study aims to achieve the following objectives: to analyze temporal and spatial trends in the Frost-Free Season (FFS) using daily minimum temperature data recorded at seven meteorological stations in the Meriç-Ergene Basin, an agriculturally important region in northwestern Türkiye, between 1980 and 2024; to map the spatial distribution of the FFS using the IDW interpolation method; and to assess the potential agricultural implications of the observed frost pattern changes.

The outcomes of this analysis are expected to shed light on how shifts in frost patterns may affect regional agricultural planning, crop choices, and long-term climate change adaptation strategies.

MATERIALS AND METHODS

The Meriç-Ergene Basin is location between 40.89–41.74° N latitudes and 26.39–27.82° E longitudes. According to the Thornthwaite climate classification, Kırklareli, Edirne, Lüleburgaz, and Çorlu exhibit a dry and slightly humid climate with noticeable winter humidity, while İpsala and Malkara are characterized by a semi-humid climate with severe summer drought (Ardel et al., 1965; Eroğlu, 2022).

In this study, 45 years of daily minimum temperature data (1980–2024) recorded by the Turkish State Meteorological Service (MGM) at seven meteorological stations within the Meriç-Ergene Basin were analyzed. The geographic characteristics (latitude, longitude, and elevation) of these stations are provided in Table 1, and their spatial distribution is shown in Figure 1.

The spatial interpolation of the Frost-Free Season (FFS) was performed using the Inverse Distance Weighted (IDW) method. This method assumes that nearby points have greater influence on the interpolated values than distant points. The IDW analysis was conducted in ArcGIS 10.8 software with a power parameter of 2. A variable search radius including the seven nearest stations was used, and the output grid cell size was set to 1 km. The IDW method was selected for its simplicity, stability with limited station density, and proven reliability in regional climatological studies (Burrough & McDonnell, 1998; Li & Heap, 2014). Before the analyses, the dataset was carefully quality-checked. Missing or obviously erroneous values were identified and corrected using neighboring-station comparisons and linear interpolation when necessary. Outliers were detected using threshold-based screening, and data homogeneity was examined through visual inspection and cross-validation. These procedures ensured that the dataset was complete, consistent, and reliable for trend and spatial analyses.

Table 1. Geographic information of meteorological stations

Station No	Station Name	Latitude (°N)	Longitude (°E)	Elevation (m)
17050	Edirne	41.6767	26.5508	51
17052	Kırklareli	41.7382	27.2178	232
17054	Çorlu	41.1798	27.8160	145
17608	Uzunköprü	41.2726	26.7056	45
17631	Lüleburgaz	41.3513	27.3108	46
17632	İpsala	40.8900	26.3900	81
17634	Malkara	40.8873	26.9080	207

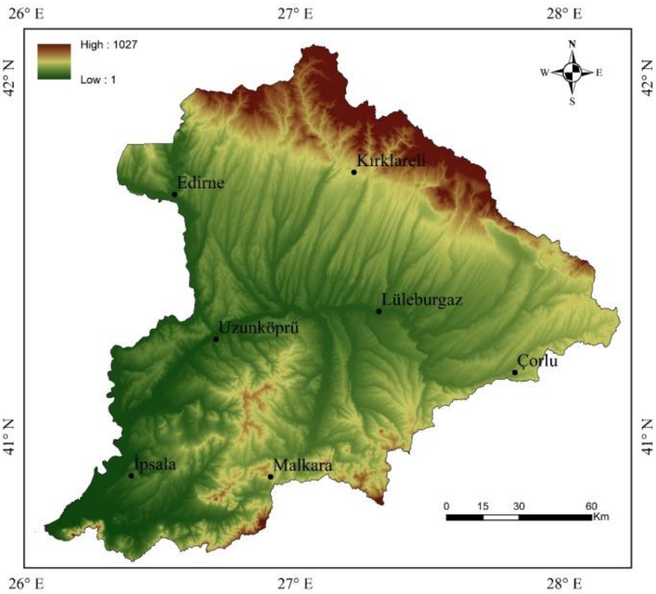


Figure 1. Locations of the meteorological stations in the Meriç-Ergene Basin

According to the definition of the World Meteorological Organization (WMO, 2011), a frost day is a day when the minimum temperature drops to 0 °C or below (Hosseini et al., 2021). In this study, LFS parameter represents the last spring frost event of the year, while FFA refers to the first autumn frost event of the year (expressed as Julian Day). The duration between these two dates defines the frost-free season (FFS). To evaluate the temporal changes (trend) of these parameters, the non-parametric Mann–Kendall test was applied to determine the statistical significance of trends, while the Sen's Slope Estimator was used to quantify the magnitude (rate of change) of these trends. Both tests were implemented using the MAKESENS Excel template developed by Salmi et al. (2002).

In the Mann–Kendall test, the null hypothesis (H_0) assumes that the data series (x_i) are independent and randomly ordered over time, while the alternative hypothesis (H_1) assumes the presence of a monotonic upward or downward trend. The Mann–Kendall test statistic (S) is calculated as shown in Equation (1) (Salmi et al., 2002):

$$S = \sum_{k=1}^{n-1} \sum_{j=k+1}^{n} sgn(x_j - x_k) \qquad \text{Equation (1)}$$

where x_j and x_k are the values in years j and k, respectively. The sign function is defined in Equation (2) as follows:

$$sgn(x_j - x_k) = \begin{cases} 1, & \text{if } x_j - x_k > 0 \\ 0, & \text{if } x_j - x_k = 0 \\ -1, & \text{if } x_j - x_k < 0 \end{cases} \qquad \text{Equation (2)}$$

When the number of observations (n) is 9 or fewer, the theoretical distribution of S, as derived by Mann and Kendall, is used (Gilbert, 1987). For n>10, the normal approximation is applied. In this case, the variance of S is calculated using Equation (3):

$$VAR(S) = \frac{1}{18}\left[n(n-1)(2n+5) - \sum_{p=1}^{q} t_p(t_p - 1)(2t_p + 5)\right] \qquad \text{Equation (3)}$$

where t_p is the number of tied groups in the data and q is the number of tied groups. The standard normal test statistic (Z) is then computed as shown in Equation (4):

$$Z = \begin{cases} \frac{S-1}{\sqrt{VAR(S)}}, & S > 0 \\ 0 & ,S = 0 \\ \frac{S+1}{\sqrt{VAR(S)}}, & S < 0 \end{cases} \qquad \text{Equation (4)}$$

Negative values of Z indicate a decreasing trend, while positive values indicate an increasing trend. The trend is considered statistically significant at a given significance level α if the absolute value of Z exceeds the critical value $Z_{(1-\alpha/2)}$ from the standard normal distribution table. In this study, a significance level of $\alpha = 0.05$ was used. Finally, the magnitude of the trend (β) is calculated using the Sen's Slope Estimator, as shown in Equation (5)

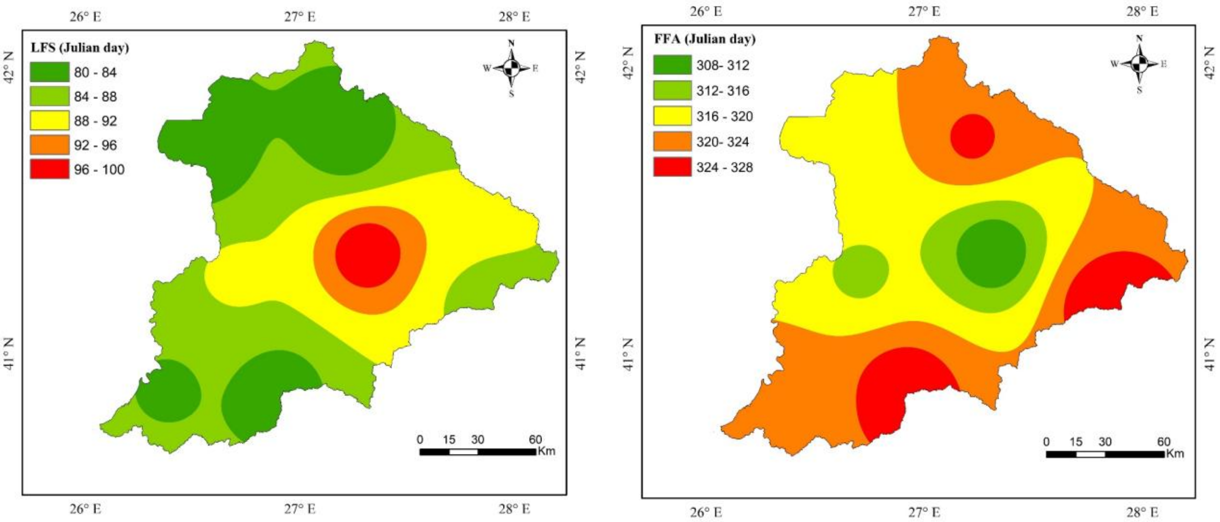
$$\beta = \text{Median}\left(\frac{x_j - x_k}{j-k}\right),\ \forall\ j > k \qquad \text{Equation (5)}$$

RESULTS AND DISCUSSION

Results

Spatial Distribution of the Frost-Free Season

In the study area, the average spring last frost dates (LFS) range between March 20 and April 9. The LFS tends to occur later as one moves from west to east and from coastal areas toward inland regions. The average fall first frost dates (FFA) range between November 4 and November 24. In the central and western parts of the basin, frosts begin earlier, whereas in the northern, southern, and eastern parts, the onset of frosts is later. Based on these two parameters, the average frost-free season (FFS) varies between 7 and 8 months across the basin. The spatial distribution of the FFS closely resembles that of the FFA. Specifically, the southeastern and northeastern parts of the basin experience longer frost-free periods, while the duration decreases toward the central inland areas. The spatial distribution of the LFS, FFA, and FFS parameters is illustrated in Figure 2.



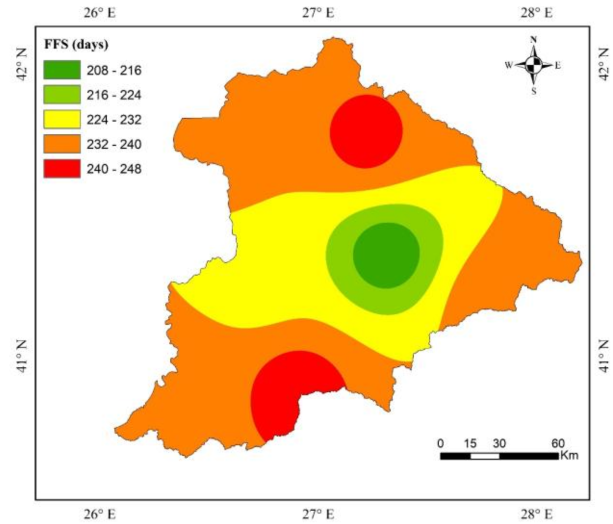


Figure 2. Spatial distribution of the LFS, FFA and FFS parameters in the Meriç-Ergene Basin

Temporal Trends of the Frost-Free Season

The temporal trend analysis of daily minimum temperature data between 1980 and 2024 (45 years) indicates that, except for the Uzunköprü and Çorlu stations, the LFS has shown a declining trend, suggesting that the last spring frost is occurring earlier in most of the basin. Among the stations, the İpsala station, located in the southern part of the study area, exhibited the most significant decline, with a trend of −4.3 days per decade, which is statistically significant at the 95% level. In contrast, the FFA has exhibited a positive trend (occurring later) at all stations during the same period. These increasing trends were found to be statistically significant at all stations except for Lüleburgaz. The most pronounced delay in the FFA was observed at İpsala, with an increase of approximately 6.7 days per decade. As a combined effect of the earlier LFS and delayed FFA, the FFS duration has shown a significant increasing trend, indicating a lengthening of the frost-free season across the basin. These increasing trends were statistically significant at all stations except Uzunköprü (4.5 days per decade). The largest increase in the FFS was recorded at İpsala, where the FFS extended by 9.6 days per decade. This analysis indicates that the delay on the FFA plays a more dominant role than the advance of the LFS on lengthening the frost-free period. The temporal trends of the LFS, FFA, and FFS parameters across the basin are illustrated in Figure 3.

Table 2. The magnitudes of trends in LFS, FFA and FFS during 1980-2024 in the Meriç-Ergene Basin

Station No	Station Name	LFS (days/decade)	FFA (days/decade)	FFS (days/decade)
17050	Edirne	-0.51	**6.11**	**6.93**
17052	Kırklareli	-2.25	**4.81**	**8.40**
17054	Çorlu	0.50	**6.15**	**5.77**
17608	Uzunköprü	0.00	**4.58**	4.52
17631	Lüleburgaz	-3.33	4.00	**8.18**
17632	İpsala	**-4.33**	**6.67**	**9.60**
17634	Malkara	-1.50	**6.20**	**8.64**

Trend values that are statistically significant at the 95% level are indicated in bold.

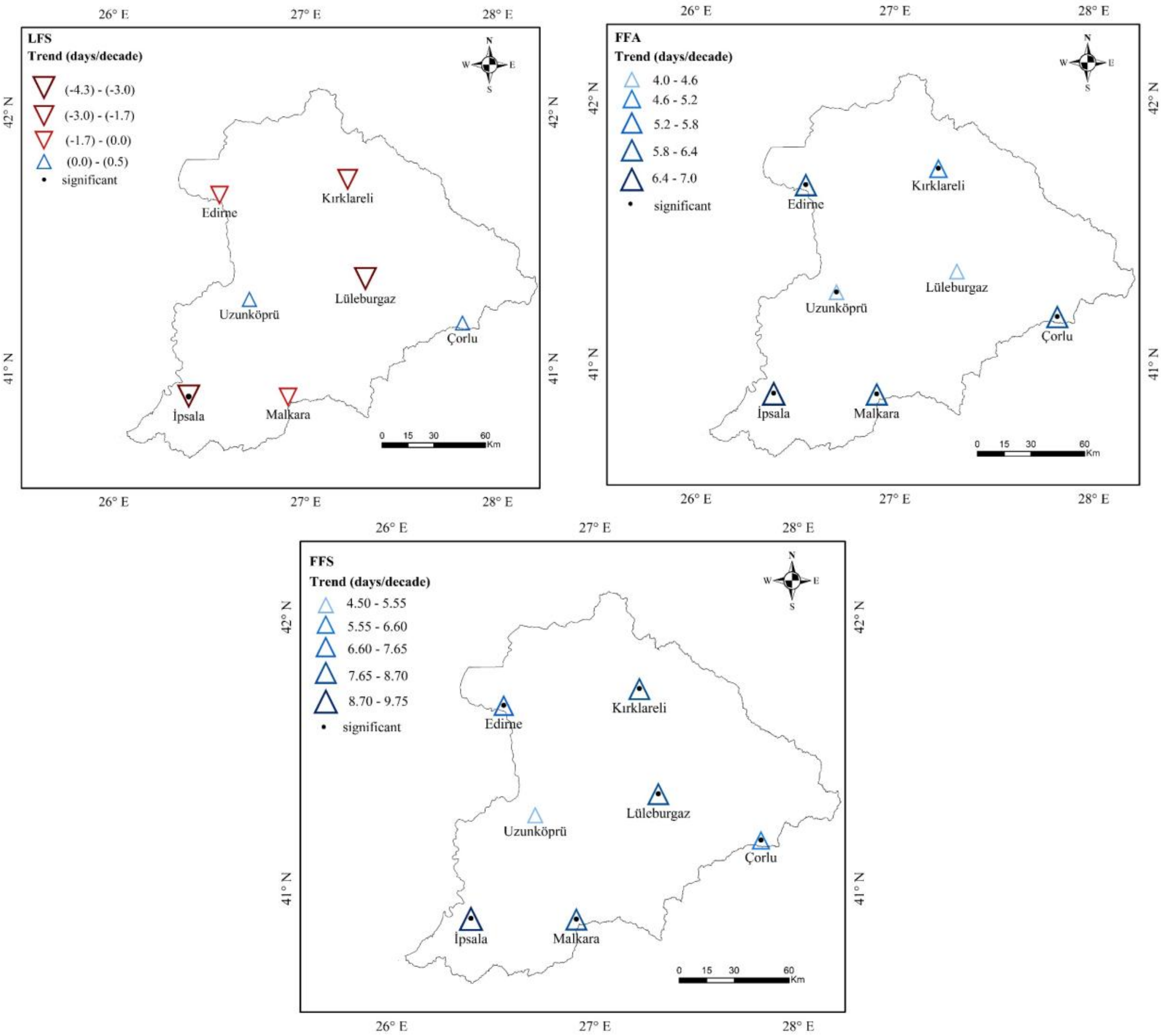


Figure 3. Temporal variations of the LFS, FFA, and FFS parameters in the Meriç-Ergene Basin

Discussion

This study examined the spatio-temporal changes of frost-free seasons using 45 years of daily minimum temperature data from 7 stations in the Meriç-Ergene basin between 1980 and 2024. Across the region, the last frost in spring (LFS) and first frost day in autumn (FFA) occurred on average on March 27 and November 15 respectively. As a result, the frost-free season (FFS) lasted an average of 7.6 months. Long-term trend analysis revealed that while LFS shifted backward by approximately 7.3 days, FFA advanced by approximately 25 days during 1980-2024. Consequently, the FFS extended by 33 days, primarily due to the more pronounced influence of the FFA on this increase.These results are an important indicator of increasing temperatures due to climate change.

Investigations from different regions of the world have revealed consistent outcomes, aligning closely with the present findings. At the national scale, Erlat and Türkeş (2016) reported a decline in the number of frost days, an earlier end to spring frosts, and a significant extension of the FFS across Türkiye in the 1950–2013 period Additionally, they emphasized strong correlations between these changes and large-scale atmospheric circulation patterns, particularly the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO). In the Meriç-Ergene Basin, the observed lengthening of the FFS may similarly be linked to anomalous circulation patterns during late winter and early spring. In addition, linking these frost-free season (FFS) changes to agricultural activities in the Meriç-Ergene Basin provides practical insights into their local implications. The basin hosts extensive cultivation of wheat, sunflower, and rice, crops that are highly sensitive to frost timing and growing season length. An extended FFS could allow earlier sowing of sunflower and wheat, while also influencing irrigation scheduling and harvest timing for rice production.

Evidence from Asia shows similar tendencies. Ning et al. (2017) reported an extension of the FFS from approximately 80% of 823 stations across China between 1951 and 2012. Nevertheless, in certain regions this prolongation can be attributed to the influence of the early LFS, whereas in others it stems from the effect of the late FFA. The İpsala station in Meriç-Ergene Basin, with an observed FFS increase of 9.6 days per decade, mirrors the high extension rates observed in northern China. Li et al. (2022), using ERA5-Land reanalysis data for the 1950–2020 period, reported that the number of frost-free days across China increased by an average of 1.25 days per year, while the number of frost days decreased by 1.41 days per year. The most rapid extensions were observed in subtropical monsoon climate zones, while more temperate regions exhibited slower rates of change. This spatial variability is consistent with the findings for the Meriç-Ergene Basin, where the FFS lengthens more noticeably in coastal and low-elevation areas, while changes are more moderate in inland locations.

Comparable patterns have also been identified on other continents. In Central and Southeastern Europe for the 1950–2019 period, a significant lengthening on the FFS was also reported. In contrast to our findings, this extension was primarily attributed to a delayed LFS (Chervenkov and Slavov, 2022). In the USA, the FFA occurred later (5.4 days/century) and the LSF earlier (6.9 days/century), resulting in an average extension of the FFS of 12.7 days/century between 1900 and 2014 (Kukal and Irmak, 2018). In Iran, except for the central and southern regions, frost started later and ended earlier, shortening the frost duration between 1987 and 2019 (Hosseini et al, 2021). The results indicate that local topography and regional atmospheric patterns are key factors playing crucial roles in shaping the observed trends.

CONCLUSION

From an agricultural standpoint, the lengthening of the frost-free season (FFS) expands the window for crop growth and can increase the yield potential of major crops such as wheat, sunflower, maize, and certain fruit and aromatic species. Yet, this apparent opportunity comes with an important caveat: if crops enter sensitive phenological stages too early, they may be exposed to unexpected late spring frosts, which can cause severe yield losses. In this sense, the extension of the FFS represents both a chance to improve production and a risk that requires careful management. This study provides the first comprehensive spatio-temporal evaluation of frost-free season variability in the Meriç–Ergene Basin, offering novel insights into regional agricultural planning and climate adaptation strategies.

The length of the frost-free season is closely similar to agricultural productivity, and detecting its changes is essential for formulating future adaptation strategies and management practices (Mapfumo et al., 2023). This study provides the first comprehensive spatio-temporal assessment of frost-free season changes in the Meriç–Ergene Basin, offering novel insights that have not been addressed in previous national or regional studies. The results from the Meriç–Ergene Basin clearly point to regional warming in line with global climate change. Looking ahead, more detailed analyses are needed to fully capture the agricultural implications. These should include agroclimatic indicators such as growing degree days (GDD), soil moisture dynamics, evapotranspiration, and indices on extreme temperature events. At the same time, spatial modeling that combines topographic characteristics (elevation, slope, and proximity to the sea) with large-scale teleconnection indices (e.g., NAO, AO) will provide a stronger scientific basis for designing effective adaptation measures. Such an integrated approach will help farmers and policymakers develop more resilient cropping patterns and long-term strategies for agricultural planning under a changing climate.

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Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contributions

Ebru Elif ARSLANTAŞ CİVELEKOĞLU: Conceptualization; data curation; formal analysis; investigation; methodology; project administration; software; writing—original draft; writing—review and editing.

Umut MUCAN: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; software; writing—original draft; writing—review and editing.

ORCID

Ebru Elif ARSLANTAŞ CİVELEKOĞLU **http://orcid.org/0000-0003-4217-9179**
Umut MUCAN **http://orcid.org/0000-0002-7126-9774**

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