Theoretical and Applied Climatology (2026) 157:140
https://doi.org/10.1007/s00704-025-05988-w

RESEARCH

Spring frost frequency increased in North America but decreased in Eurasia from 1948 to 2016

Wei Guo[1,2] · Chuhan Lu[3] · Ping Xia[4] · Lijiang Fu[1,2] · Govindjee Govindjee[5] · Hao Tang[6] · Jian Chen[1,2] · Li Song[7] · Jinglu Tan[8] · Zhenyu Xu[9] · Ya Guo[1,2]

Received: 18 March 2025 / Accepted: 13 December 2025

Abstract

The impacts of spring frost on agricultural production and plant ecology have been frequently reported; however, understanding of the spatial and temporal distribution patterns and changes in trends of spring frost events on large scale remains limited. In this work, we explore the spatiotemporal variations of spring frost events in North America and Eurasia from 1948 to 2016. The frequency of spring frost has increased in North America, while it has decreased in Eurasia. The percentage of regions with increased spring frost is increasing in North America, whereas it is decreasing in Eurasia. It was also found that the frequency of cropland experiencing spring frost is rising in North America, whereas it is falling in Eurasia. The changes in the temporal and spatial distributions of spring frost events raise the question whether they are triggering changes in agriculture management and potential gains and losses as the world becomes warmer, especially in regions where the risk of spring frosts is increasing.

Keywords Spring frost · Agriculture · Climage change · Remote sensing

✉ Ya Guo
guoy@jiangnan.edu.cn

1 Key Laboratory of Advanced Process Control for Light Industry, Ministry of Education, Jiangnan University, Wuxi 214122, China

2 International Joint Research Center for Intelligent Optical Sensing and Applications at Jiangnan University, Jiangnan University, Wuxi 214122, China

3 Key Laboratory of Ecosystem Carbon Source and Sink, China Meteorological Administration (ECSS-CMA), Wuxi University, Wuxi 214063 , China

4 Key Laboratory of Meteorological Disaster, Ministry of Education, Nanjing University of Information Science and Technology, Nanjing 210044, China

5 Center of Biophysics & Quantitative Biology, Department of Biochemistry and Department of Plant Biology, University of Illinois at Urbana-Champaign, Urbana, IL 61801, USA

6 Chloview Technology (Wuxi) Co., Ltd, Wuxi214100, China

7 Joint International Research Laboratory of Agriculture and Agri-Product Safety, Yangzhou University, Yangzhou 225009, China

8 Department of Biomedical, Biological & Chemical Engineering, University of Missouri, Columbia, MOP 65211, USA

9 Longcom Internet of Things Co. Ltd, Hefei230088, China

1 Introduction

Over the past 50 years, even as the earth's average surface temperature has risen approximately 0.9 °C globally (Lu et al. 2020), spring frosts have remained a major global concern (Clayton and Karazsia 2020; Giorgi. 2019; Tanir et al. 2024). They disrupt the natural cycles of plants and animals and pose significant threats to agriculture, human health, and ecosystems (Cowherd et al. 2023; Eekhout and Vente 2019; Lima et al. 2021; Paul & Macadam 2021; Sales et al. 2024; Tilburg and Hudson 2022; Viana et al. 2022). Spring frosts, characterized by temperatures below 0 °C in spring, are among the most extreme weather events, with a large impact, but have not been fully investigated (Allevato et al. 2019; Augspurger 2013; Bascietto et al. 2018; Holman et al. 2011). Spring frost events primarily occur in the Northern Hemisphere (Liu et al. 2018). However, the Eurasian continent and North America exhibit significant differences in geography, climate, and landforms (Hong 1999). These differences are likely to induce significant differences in the frequency and the scope of the impact of spring frost events around the Northern Hemisphere. Seasonal crops that are planted during fixed time intervals at global locations, and the seeds that may not be originally from the same

Published online: 14 February 2026

vicinity, reduce the crops' ability to adapt to spring frosts at their new locations (Vitasse et al. 2018a). For example, as the planet warms, tropical crops are increasingly cultivated in sub-tropical and temperate regions of the world increasing their vulnerability to sudden snaps of spring frosts. With increasing frequency of spring frost, cellular damages in crops increase.

Temperature data is used as an indicator of spring frost in analyzing and assessing risks from it (Augspurger 2013). For example, Crimp et al. (2016) have analyzed the changes in the number of frost events in different months to assess the risks that crops may face after planting. Xiao et al. (2018) used the accumulated number of days of spring frost as an index to measure the rate of spring frost and its impact on crop yields. To reduce the negative impact of spring frost on agriculture, Lamichhane (2021) suggested that it is necessary for the assessment of the frequency and the severity of spring frosts to support the formulation of management and policy strategies in land and agriculture. All these studies have emphasized the importance and the necessity of studying the changes in timing of occurrences of spring frost, especially for evaluating its impact on agriculture.

At present, information on spring frosts has relied on localized, small-scale studies, from around the world, providing inconsistent conclusions. Intuitively, while it may appear that as the planet warms, spring frost events would decrease (Wang et al. 2011; Zhou and Ren 2012), but in reality the published literature suggests a much more complicated situation, with the risk of spring frosts varying widely across geographical regions (Augspurger. 2013; Cannell and Smith 1986; Eccel et al. 2009; Hoffmann and Rath 2013; Kaukoranta et al. 2010; Leolini et al. 2018; Unterberger et al. 2018; Zhong et al. 2007).

Therefore, this study aims at conducting a global analysis of spring frost events to obtain a more comprehensive understanding of their spatiotemporal patterns and potential impacts under climate change. Since most of the long-term global food production is primarily concentrated in North America and in Eurasia (Potapov et al. 2022; Ramankutty et al. 2002), we concentrate our assessment to these regions. We have used long-term historical climate data to conduct quantitative analysis of the variation patterns of the number of spring frosts and their impact on agriculture (Crimp et al. 2016; Xiao et al. 2018). These quantitative analyses provide us with crucial insights for formulating global agricultural risk management strategies. Here, we specifically use satellite remote sensing derived time series data of two temperature datasets from the Northern Hemisphere from 1948 to 2016 (Dunn et al. 2020; Rodell et al. 2004; Sheffield et al. 2006) to investigate the occurrences of spring frosts in terms of: (1) temporal and spatial distributions of spring frosts in North America and Eurasia in the Northern Hemisphere, (2) the change of risk probability of spring frost events in North America and Eurasia, and (3) analysis of the impact of spring frost on cropland in North America and Eurasia.

2 Methods

2.1 Data acquisition

(1) *Princeton dataset*

The daily temperature data used in this work are with 0.25-degree resolution produced by the Terrestrial Hydrology Research Group from the Princeton University (available from https://hydrology.soton.ac.uk/). These datasets were corrected by combing observation-based records with the "reanalysis data" from the National Center for Environmental Prediction and the National Center for Atmospheric Research (NCEP/NCAR) (Sheffield et al. 2006). These data have already been successfully applied in the studies of climate changes in the literature (Liu et al. 2018; Zhang et al. 2018).

(2) *HadEX3 dataset*

HadEX3 dataset contains data on land-based climate extremes (data available from https://www.metoffice.gov.uk/hadobs/hadex3/download_etccdi.html; see: Dunn et al. 2020; Dunn et al. 2022). Among the above dataset, there is one named '*frost days*' that can be used for the study of spring frost events. Its spatial resolution (latitude and longitude) is 1.25-degree x1.875-degree, and the temporal resolution is one month. The indices, thus obtained, represent seasonal and/or annual values derived from daily station data.

(3) *Cropland data*

These data are available from: https://developers.google.com/earth-engine/datasets/catalog/USGS_GFSAD1000_V1#bands; they are provided by Global Food-and-Water Security-support Analysis Data (GFSAD) site, which is a NASA. funded project to provide highest-resolution global cropland data.

2.2 Extraction of spring frost events

In this work, Spring Frost (SF) events are defined when the temperatures are below 0 °C in the spring (Liu et al. 2018).

Since the analysis covers the entire Northern Hemisphere, spring was defined as the period from March 1 to May 31 in this work. The temperature data were extracted from the Princeton dataset for the months of March, April, and May each year for each location. The extracted temperature data were then used to calculate the number of times the temperature was below 0 °C during these months for each grid. Through this operation, the number of spring frost events for each month was extracted for each location (*Latitude (Lat)*, *Longitude (Lon)*), which was denoted as $N_{Lat,Lon,M,Y}$.

$$\begin{aligned} &3 \leqslant M \leqslant 5 \\ &Year = [1948,\ 1949,\ \cdots,\ Y,\ \cdots,\ 2015,\ 2016] \end{aligned} \tag{1}$$

M refers to one of the three months (March (*M*=3), April (*M*=4), and May (*M*=5)) of the spring season, whereas, *Y* refers to a specific year between 1948 and 2016.

2.3 Variations in number of spring frosts with time

The change in the number of spring frosts for a month and location (*Lat*, *Lon*) can be calculated by linear regression as follows:

$$N_{Lat,Lon,M,Y} = k_{Lat,Lon,M,Per}Y + b_{Lat,Lon,M,Per} \tag{2}$$

where $N_{Lat,Lon,M,Y}$ is the number of spring frost events corresponding to year *Y* and month *M* at location (*Lat*, *Lon*); $b_{Lat,Lon,M,Per}$ is the intercept; and *Per* (period) refers to a specific time period between 1948 and 2016. The significance of the slope assessed using a standard t-test ($p<0.05$), and its standard error reflects the uncertainty of the estimate. The coefficient of determination (R^2) indicates the proportion of variance in the observed data explained by the linear model, reflecting the goodness of fit. Further, $k_{Lat,Lon,M,Per}$ is the slope of linear regression. The frequency of spring frosts varies depending on the value of $k_{Lat,Lon,M,Per}$. Specifically, when $k_{Lat,Lon,M,Per}$ is greater than zero, it indicates increased frequency of spring frost. The locations with $k_{Lat,Lon,M,Per} > 0$ is defined as ISF (Increased Spring Frosts) region in this work. Conversely, a region with negative $k_{Lat,Lon,M,Per}$, indicating a decrease in spring frost frequency, is classified as a DSF (Decreased Spring Frost) region. If $k_{Lat,Lon,M,Per}$ is equal to zero, spring frosts do not change with time, which usually indicates that the temperatures at a location were always above or below 0 °C in the three-month period, and these regions are defined as NSF (No Change Spring Frosts).

2.4 Application of a sliding time window

Given the randomness and scattered nature of spring frost events, it is necessary to conduct long-term analysis to reveal the temporal and spatial evolution patterns of ISF (Increased Spring Frost) regions, thereby providing a more thorough understanding of their evolutionary trends. Therefore, the method of a sliding time window of 30 years (Hawkins and Sutton 2012), incrementing by 1 year each step from 1948 to 2016, was used to study the change of risk of spring frost. The time window may be represented as a vector, *Pe*, as shown below.

$$Pe = \begin{bmatrix} 1948 & 1949 & \cdots & 1976 & 1977 \\ 1949 & 1950 & \cdots & 1977 & 1978 \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ 1967 & 1968 & \cdots & 1985 & 1986 \\ 1968 & 1969 & \cdots & 1986 & 1987 \\ \vdots & \vdots & \cdots & \vdots & \vdots \\ 1986 & 1987 & \cdots & 2014 & 2015 \\ 1987 & 1988 & \cdots & 2015 & 2016 \end{bmatrix}_{40\times 30} \tag{3}$$

Further, *PN* is the row number in *Pe*, as Eq. (4).

$$PN = [1, 2, 3, , \cdots, Per,\ \cdots, 38, 39, 40] \tag{4}$$

In this context, *Per* refers to the ordinal number of a specific period. For instance, *Per* = 1 indicates the first period, encompassing the years from 1948 to 1977, which corresponds to the first row in matrix *P*e. After applying a 30-year sliding windows, the data from 1948 to 2016 yield 40 time windows of 30 years. We use the first 20 time windows to represent 1948–1996 (Period 1), and the second 20 time windows to represent 1968–2016 (Period 2). Within both the periods, there are 20 distinct periods, each corresponding to a distribution of ISF (Increased Spring Frost) regions. In each period, there will be a corresponding $k_{Lat,Lon,M,Per}$ for each position. By counting the 20 consecutive periods within Period 1, we calculate the number of times that the $k_{Lat,Lon,M,Per}$ is greater than 0. Then, we divide this number by 20 (the total number of periods during Period 1 (or Period 2)) to obtain value for a proportion, which represents the probability of an area as ISF region in Period 1 (or Period 2). This probability is denoted as $P_{SF,Lat,Lon,M,\text{Period1}}$ (or $P_{SF,Lat,Lon,M,\text{Period2}}$). To analyze the differences between the two periods, the means of the probabilities in Eurasia and North America for the two periods were compared by t-test. Similarly, we can utilize the same approach to calculate the number of occurrences where the position of a cropland region satisfies $k_{Lat,Lon,M,Per} > 0$ across the 20 periods within Period 1 (or Period 2). We are thus able to determine the probability of a specific cropland located in the ISF regions during Period 1 (or Period 2), which has been denoted as $P_{Crop,Lat,Lon,M,\text{Period1}}$ (or $P_{Crop,Lat,Lon,M,\text{Period2}}$).

2.5 Calculation of the percentage of cropland located in regions with increased frequency of spring frost

For a specific time period (*Per*), $k_{Lat,Lon,M,Per}$ is calculated for each grid within that time period, and then the percentage of cropland located in ISF (increased spring frost) regions in North America (or Eurasia) to the total cropland area in North America (or Eurasia) is computed during that time period. This percentage is denoted as $P_{NA,M,Cropland,Per}$ (or $P_{Eu,M,Cropland,Per}$). To analyze whether $P_{NA,M,Cropland,Per}$ (or $P_{Eu,M,Cropland,Per}$) is increasing or decreasing over time, a linear regression model is used to study the relationship between $P_{NA,M,Cropland,Per}$ ($P_{Eu,M,Cropland,Per}$) and *Per* to determine the trend.

3 Results

3.1 Temporal and Spatial distributions of spring Frost events from 1948 to 2016

The probability of spring frost events occurring is shown to be continuously decreasing from 1948 to 2016 for all the three months (March, April, and May) in the Northern Hemisphere land masses (Fig. 1). Although the overall trend of spring frost in the Northern Hemisphere is decreasing, some regions may show increased probability of spring frost occurrence. To confirm this, the temperature data from 1948 to 2016 were used to study the variation of spatial distributions of spring frost events in the Northern Hemisphere, which were divided into two periods, 1948–1982 and 1983–2016, for better comparison of the spatial distribution differences of the number of spring frost events. To map the changes in the number of spring frost events during 1948–1982 and during 1983–2016 across the Northern Hemisphere, the number of spring frost events for March, April, and May of each year at each location was computed by using the gridded data (Spatial resolution: 0.25 degrees, Temporal resolution: daily) on daily minimums (for details, see Methods).

The slopes ($k_{Lat,Lon,M,Per}$) of the number of spring frosts with respect to years are shown in Fig. 2. The areas were separated into three categories according to the number of spring frost events at a location in the analyzed period: the number of spring frosts increased (ISF, $k_{Lat,Lon,M,Per} > 0$, $p<0.05$), decreased (DSF, $k_{Lat,Lon,M,Per} < 0$, $p<0.05$), or did not change (NSF, $k_{Lat,Lon,M,Per} = 0$), where $k_{Lat,Lon,M,Per}$ is the slope of the number of spring frosts with respect to time (year), and *p* is the significance of regression (See Methods and Supplementary S1 and S2). The NSF areas are mostly near the Arctic or in the tropics, which is expected because the tropical areas have high temperatures year-round and are unlikely to have spring frosts, and the temperature is almost always below 0 °C in March and April near the Arctic. Our primary focus, however, is on the distribution of ISF regions, areas with increasing spring frosts. The ISF regions are basically distributed only in North America and Eurasia (Fig. 2). Therefore, we focus on analyzing the characteristics of ISF distribution in these two continents. The distribution of ISF regions in both Eurasia and North America exhibit scattered and random distribution patterns. We processed the HadEX3 dataset with the same method, as used above, and found very similar conclusions, as noted above (Supplementary S3).

3.2 The change in the trend of areas with increased spring frost in Eurasia and North America

In North America, compared with Period 1, the probability of being an ISF region in Period 2 increased in more regions, especially in March and May (Figs. 3A to F).

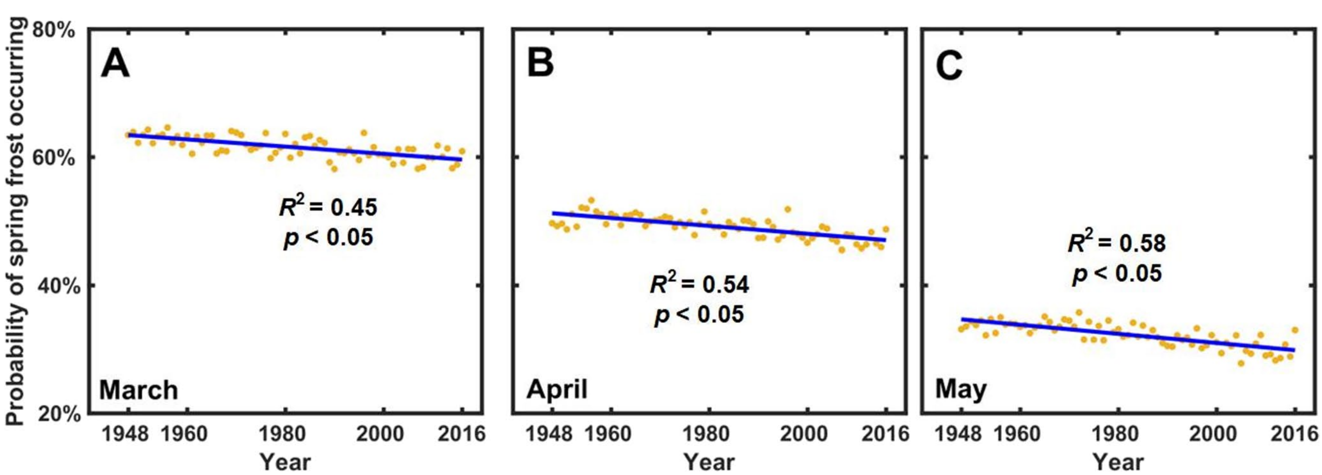

Fig. 1 The probability of spring frost occurring each year for the months of March (**A**), April (**B**), and May (**C**) from 1948 to 2016 in the Northern Hemisphere land masses

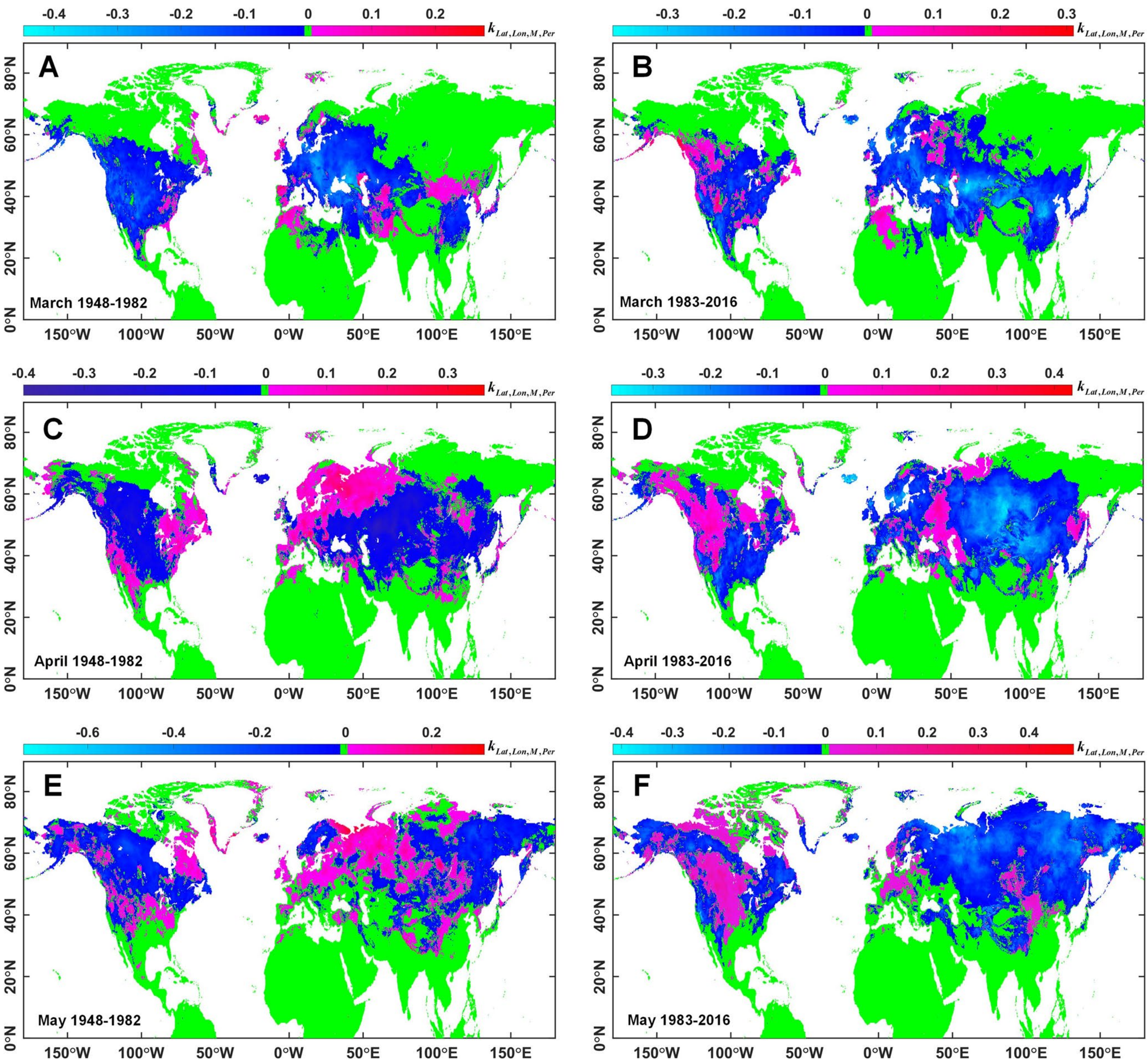

Fig. 2 The geographic distribution of frequency of spring frosts in the Northern Hemisphere, calculated from the Princeton dataset. The number of spring frost events increased (ISF, $k_{Lat,Lon,M,Per} > 0$, $p<0.05$, red color), decreased (ISF, $k_{Lat,Lon,M,Per} < 0, p<0.05$, blue color), or showed no change (NSF, $k_{Lat,Lon,M,Per} = 0$, green color). (**A**) March 1948–1982. (**B**) March 1983–2016. (**C**) April 1948–1982. (**D**) April 1983–2016. (**E**) May 1948–1982. (**F**) May 1983–2016. Note that $k_{Lat,Lon,M,Per}$ is the slope coefficient in the linear regression of the number of spring frosts vs. time (see Methods and Supplementary Figs. S1 and S2)

Specifically, in March, the average probability of each area as ISF region significantly increased from 11.46% in Period 1 to 34% in Period 2 ($p<0.01$) (Fig. 3G). Then, in April, although the average probability increased, the increase was relatively small, rising from 19.04% to 22.28% ($p<0.01$) (Fig. 3G). However, in May, rose from 23.37% in Period 1 to 34.5% in Period 2 ($p<0.01$) (Fig. 3G). For HadEX3 dataset, the calculated results are consistent with the results from the Princeton dataset ($p<0.01$) (Supplementary S4). Consequently, we conclude that the frequency of spring frost has recently increased in the western region (the Rockies and the Prairies) of North America.

In Eurasia, compared with Period 1, Period 2 showed a reduction in the probability of being an ISF region in many more regions (Fig. 4A to F). However, it is worth noting that some areas that had a relatively low probability of being an ISF region in Period 1 have experienced an increase in the probability of being an ISF region in Period 2 (Fig. 4A, B, C and D). Overall, the average

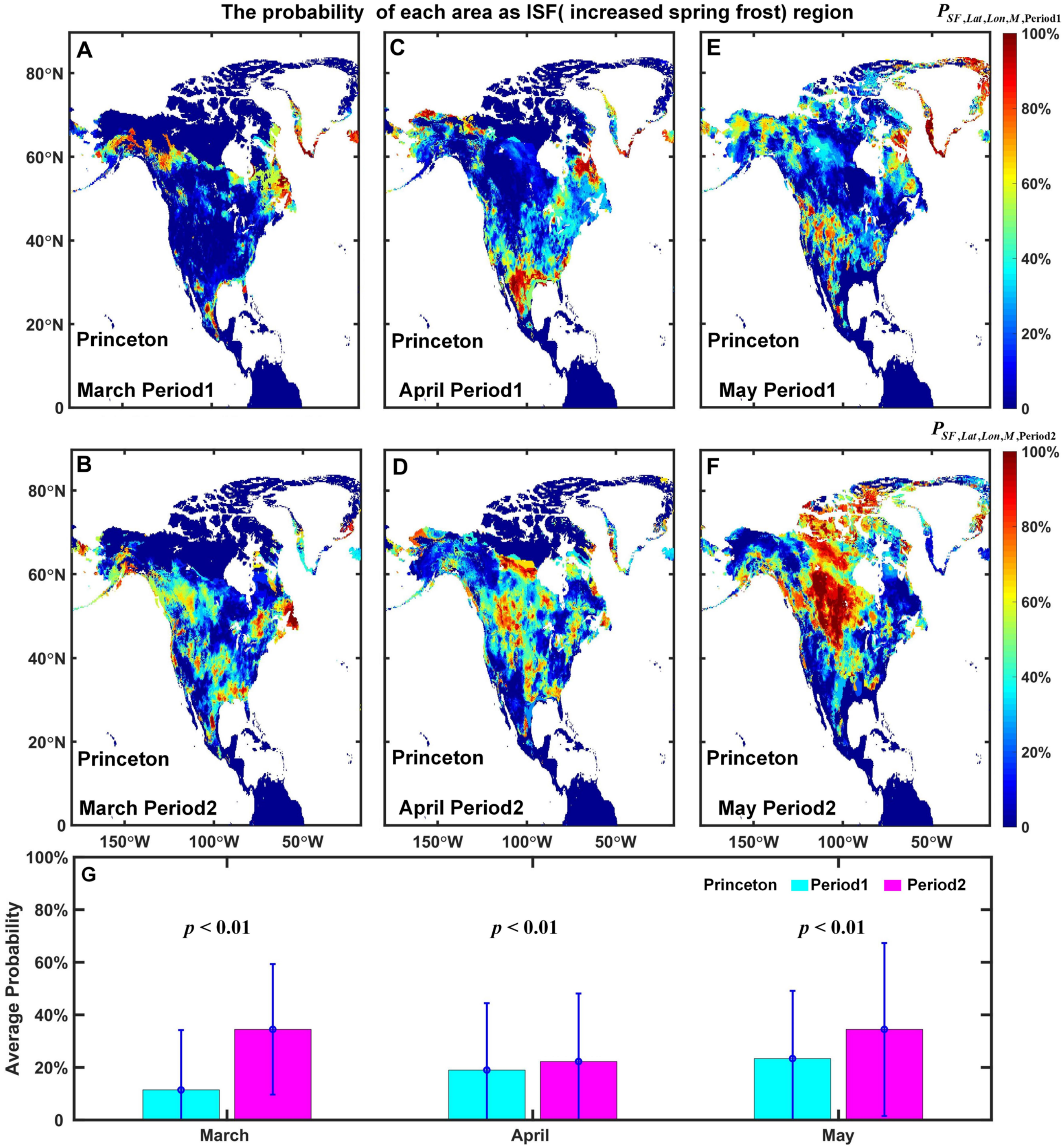

Fig. 3 The distribution of probability of each area as ISF (increased spring frost) region in North America, calculated by the Princeton dataset. (**A**) March, Period 1; (**B**) March, Period 2; (**C**) April, Period 1; (**D**) April, Period 2 (**E**) May, Period 1; (**F**) May, Period 2. (**G**) A comparison of the average probability of each area as ISF region between two time periods in North America. The color bar refers to the probability of each area as ISF region ($P_{SF,Lat,Lon,M,\text{Period1}}$(or $P_{SF,Lat,Lon,M,\text{Period2}}$)). Period 1 refers to the time span encompassing the years from 1948 to 1996, whereas Period 2 covers the period from 1968 to 2016 (See Methods)

probability of each area as an ISF region has declined. Specifically, in March, the average probability of each position as ISF region in Eurasia decreased from 19.23% in Period 1 to 15.05% in Period 2 ($p < 0.01$) (Fig. 4G). Subsequently, in April, the average probability decreased from 22.69% to 17.07% ($p < 0.01$) (Fig. 4G). In May, the average probability dropped from 27.35% in Period 1 to 15.05% in Period 2 ($p < 0.01$) (Fig. 4G). By using the

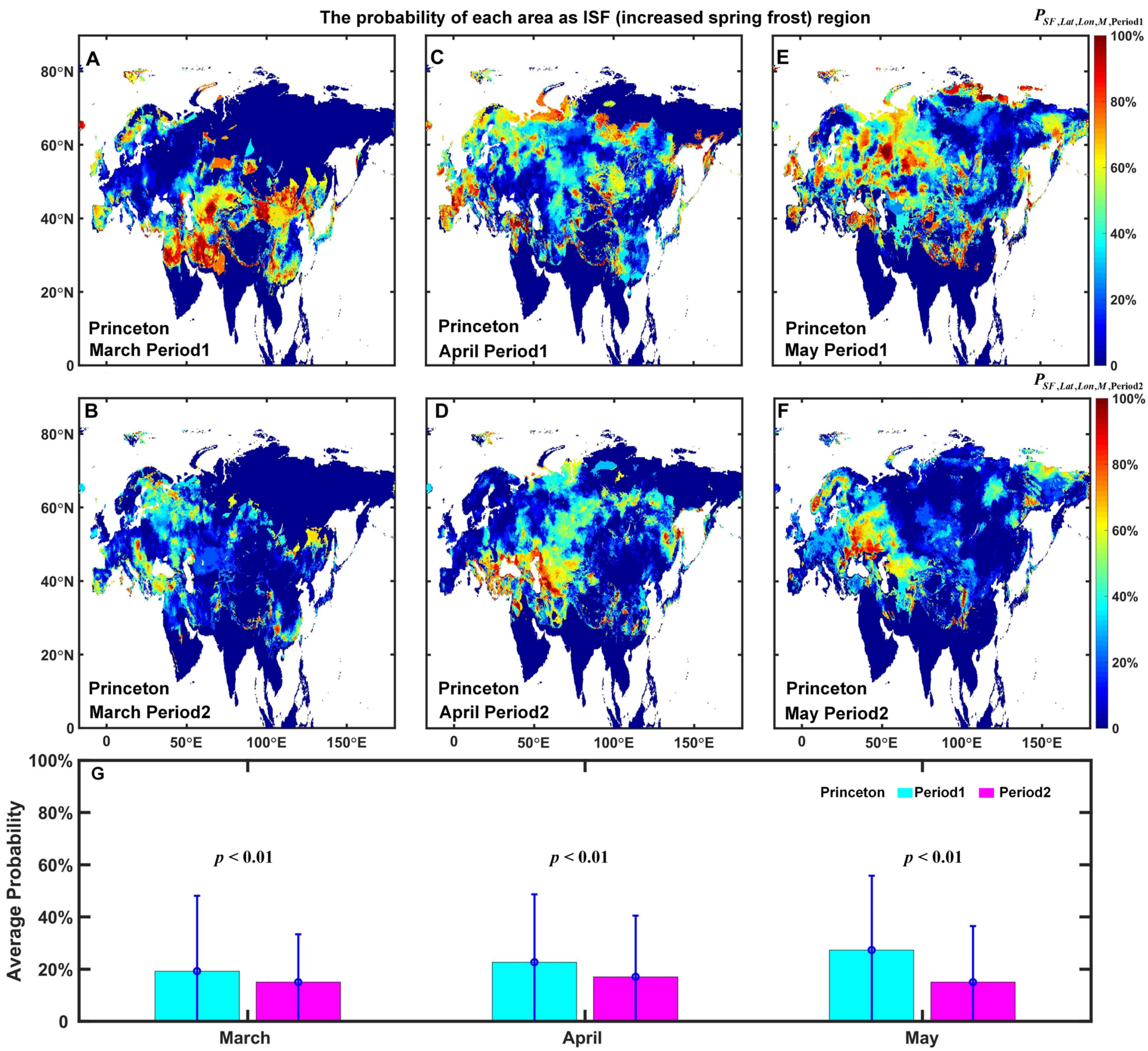

Fig. 4 The distribution of probability of each area as ISF region in Eurasia, calculated by the Princeton dataset. (**A**) March, Period 1; (**B**) March, Period 2; (**C**) April, Period 1; (**D**) April, Period 2 (**E**) May, Period 1; (**F**) May, Period 2. (**G**) A comparison of the average probability of each area as an ISF region between two time periods in Eurasia. The color bar refers to the probability of each area as ISF region ($P_{SF,Lat,Lon,M,\mathrm{Period1}}$(or $P_{SF,Lat,Lon,M,\mathrm{Period2}}$)). Period 1 refers to the time span encompassing the years from 1948 to 1996, whereas Period 2 covers the period from 1968 to 2016 (See Methods)

HadEX3 dataset, the same conclusion was also reached ($p<0.01$) (Supplementary S5). Therefore, the frequency of spring frost has decreased in Eurasia.

3.3 The impact of spring Frost on agriculture in Eurasia and North America

Croplands are mainly distributed in the low and mid-latitude regions, which are also areas with more spring frost (Supplementary S6). The percentage of croplands located within ISF (Increased Spring Frost) regions have undergone a trend of increasing over time in North America over the years for all the three months ($p<0.05$) (Fig. 5A, B and C), while in Eurasia, it has shown a downward trend ($p<0.01$) (Fig. 5D, E and F). The results calculated from the Princeton dataset are consistent with that from the HadEX3 dataset (Supplementary S7).

Further, we analyzed changes in the probability of cropland being located in ISF regions (See Methods). In North America, the probability of cropland located in ISF regions during the Period 2 is shown here to be greater than that during the Period 1, regardless of the month (Fig. 6). By calculating the average values of the probability distributions for both the periods, we have quantified this change and found that, compared to Period 1, the average probability of cropland located in ISF regions increased significantly during Period 2 ($p<0.01$) (Fig. 6G). This change indicates that the frequency of cropland experiencing spring frost is gradually increasing in North America. The findings derived from the HadEX3 dataset are shown to be in close agreement with those obtained from the Princeton dataset (Supplementary S8).

For Eurasia, in March, compared to Period 1, the probability of cropland located in ISF regions decreased significantly in the Asian part, while a small portion of cropland in Europe showed an upward trend (Fig. 7A and B). In April, during Period 2, the probability of cropland located in the ISF regions in the Western Europe decreased relative to that in Period 1, while there was an increasing trend in southern Europe. Meanwhile, the probability in Asia shows a decline (Fig. 7C, D). In May, for both Europe and Asia, the probability of cropland located in ISF regions in Period 2 shows a decreasing trend compared to Period 1 (Fig. 7D, E). By comparing the average probabilities of cropland located in the ISF regions between the two periods in Eurasia, we found that the probability significantly decreased in Period 2 compared to Period 1 for all the three months ($p<0.01$) (Fig. 7G). This indicates that the frequency of cropland experiencing spring frost is decreasing in Eurasia overall. The HadEX3 datasets also yield similar results (Supplementary S9).

4 Discussion

The ISF (Increased Spring Frost) regions are primarily concentrated in Eurasia and North America (Fig. 2). Many researchers have also conducted investigations on this topic and have discussed this issue. According to a hypothesis proposed in 1985, global warming was suggested to increase the risk of spring frost damage to trees in the boreal and temperate regions (Cannell 1985; Hänninen 2006). In the Huang-Huai regions, the frequency of spring frost has been increasing since the 1970 s (Zhong et al. 2007). Analysis of a long-term temperature record (1889–1992) in the state of Illinois in the USA also indicates that spring frost risk is increasing (Augspurger. 2013). These studies do indeed confirm that even as global temperatures rise, there are still local regions exhibiting increased risk of spring frosts. However, as the temperature rises, more regions are expected to decrease the risk of spring frost (Wang et al. 2011; Zhou and Ren 2012). This indicates that there are regions where

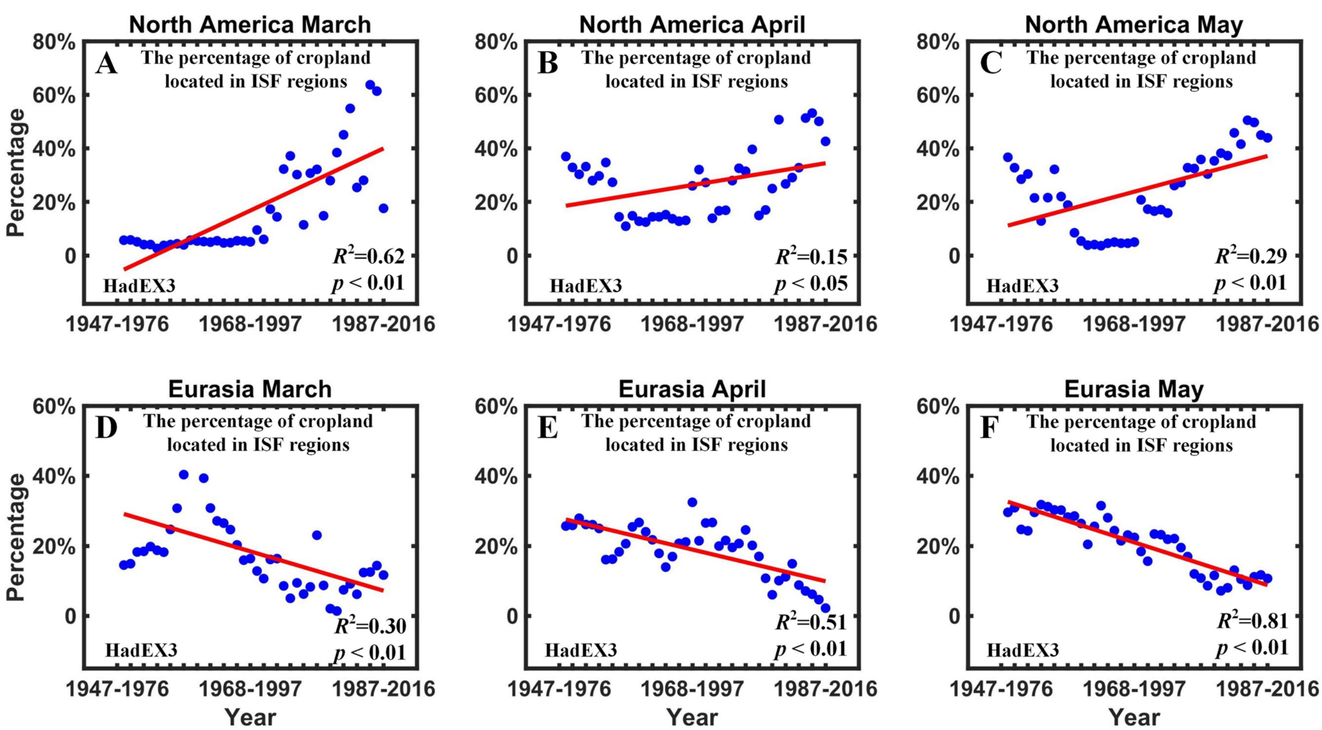

Fig. 5 The changes in trends of the percentage of cropland located in the ISF (increased spring frost) regions ($P_{NA,M,Cropland,Per}$ ($P_{Eu,M,Cropland,Per}$)see Methods) in North America and Eurasia, were calculated by using the HadEX3 dataset. **(A)** March, North America; **(B)** April, North America; **(C)** May, North America; **(D)** March, Eurasia; **(E)** April, Eurasia; **(F)** May, Eurasia

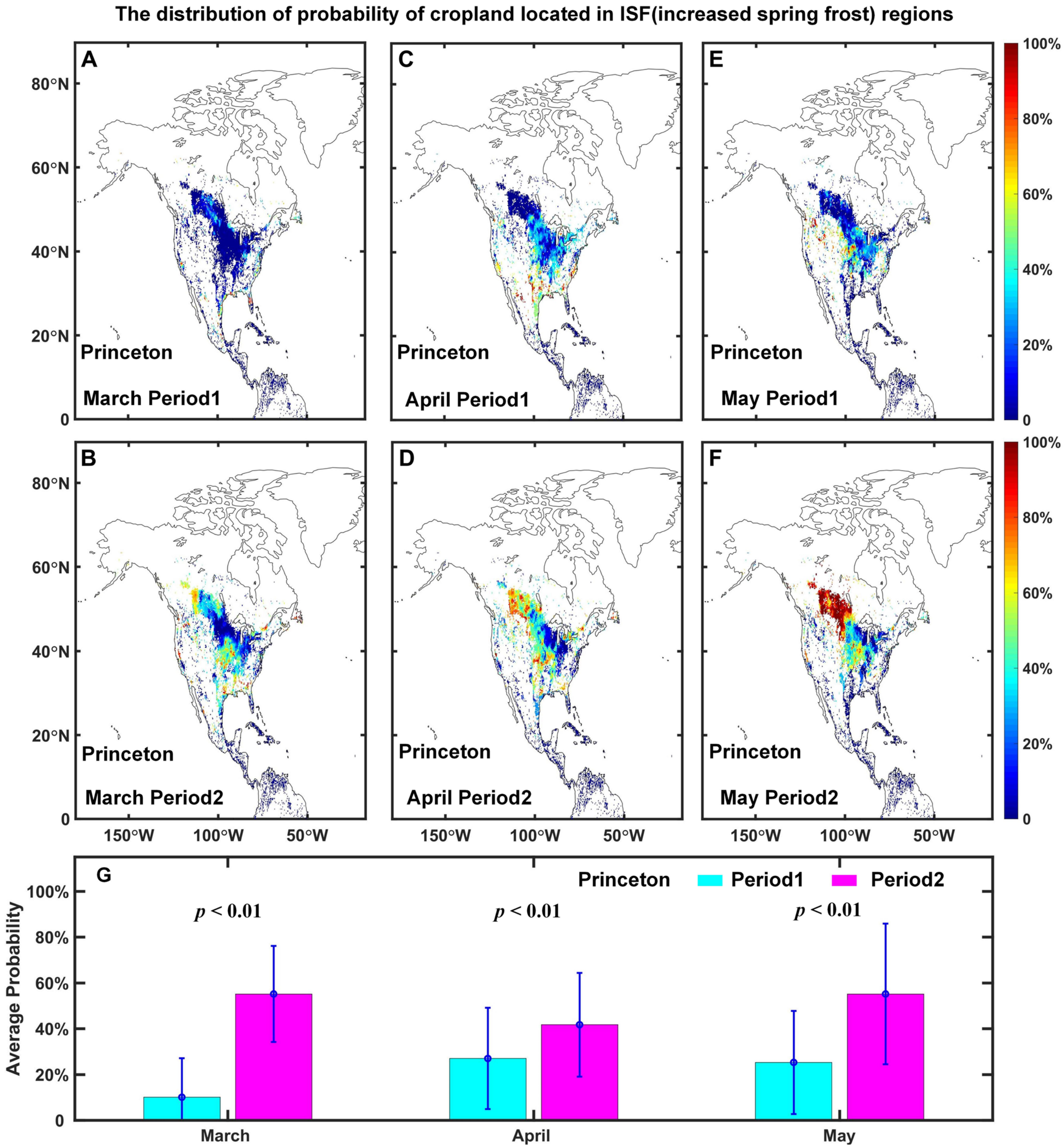

Fig. 6 **The distribution of probability of cropland located in the ISF (increased spring frost) regions in North America, calculated from the Princeton dataset**. (**A**) March, Period1; (**B**) March, Period 2; (**C**) April, Period 1; (**D**) April, Period 2 (**E**) May, Period 1; (**F**) May, Period 2. (**G**) A comparison of the average probability of cropland located in ISF regions between two time periods in North America. The color bar refers to the probability of cropland located in ISF regions ($P_{Crop,Lat,Lon,M,\mathrm{Period1}}$(or $P_{Crop,Lat,Lon,M,\mathrm{Period2}}$)). Period 1 refers to the time span encompassing the years from 1948 to 1996, whereas Period 2 covers the period from 1968 to 2016 (See Methods)

the risk of spring frosts is increasing and there are regions where the risk is decreasing. Hence, studying different regions may lead to different conclusions. In contrast, our work focuses on the variations of spring frost events on a large-scale in both North America and Eurasia, providing a clearer demonstration of the significant differences in spring frost events in these regions. This can explain why different studies have yielded diverse outcomes (Augspurger. 2013;

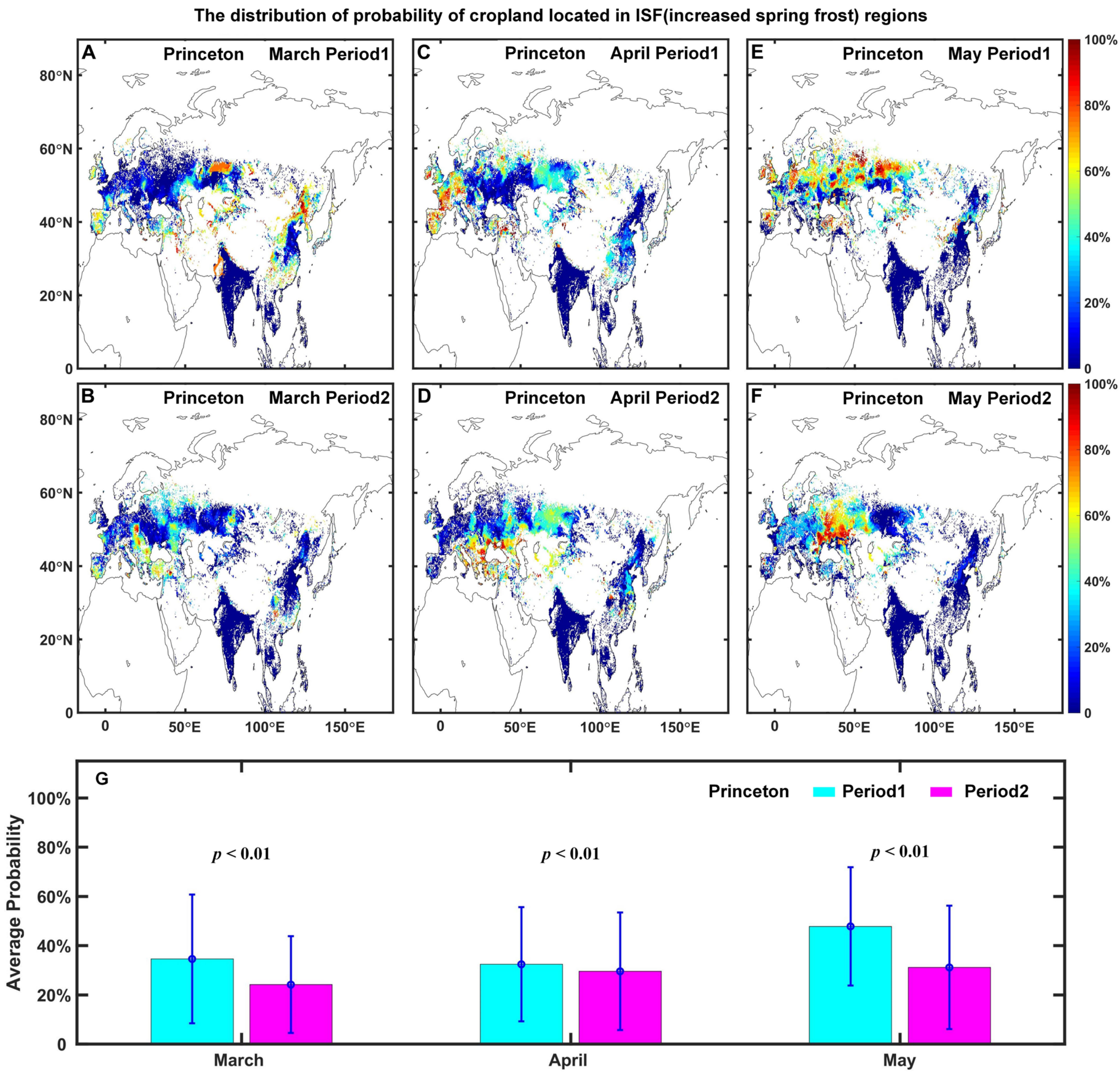

Fig. 7 **The distribution of probability of cropland located in ISF (increased spring frost) regions in Eurasia, calculated from the Princeton dataset**. (**A**) March, Period 1; (**B**) March, Period 2; (**C**) April, Period 1; (**D**) April, Period 2 (**E**) May, Period 1; (**F**) May, Period 2. (**G**) A comparison of the average probability of cropland located in ISF regions between the two time periods in Eurasia (($P_{Crop,Lat,Lon,M,\mathrm{Period1}}$(or $P_{Crop,Lat,Lon,M,\mathrm{Period2}}$))). Period 1 refers to the time span encompassing the years from 1948 to 1996, whereas Period 2 covers the period from 1968 to 2016 (See Methods)

Eccel et al. 2009; Hoffmann and Rath 2013; Unterberger et al. 2018). Therefore, it is necessary to study spring frost events on a large scale to avoid biases resulting from a limited research scope.

In the context of global warming, a decline in the risk of spring frost can be expected. Indeed, the probability of being an ISF (Increased Spring Frost) region has decreased in Eurasia. However, in North America, the probability has increased. This may be related to the lack of a barrier of transverse mountain ranges in North America, which allows cold air from the Arctic regions to move through the continent unimpeded, resulting in increasing the likelihood of spring frosts (Zohner et al. 2020). In addition, in North America, tree species in forest regions tend to adopt “cautious” leaf-out strategies, whereas in Eurasia they tend to adopt opportunistic strategies (Zohner et al. 2020), from which we may infer that spring frosts occur more frequently in North America compared to Eurasia. Our approach directly analyzes the frequency change of spring frost across the entire spring season (March to May) in North America and Eurasia, confirming that the frequency of spring frost in North America is increasing, whereas the frequency in Eurasia is decreasing. However, which specific month's spring frost events have the greatest impact on plant phenology still requires further investigation in future reserach. The impact of spring frosts on plants is not only determined by the frequency and timing of frost events, but also closely related to the developmental stage and phenology of the plants (Peterson and Abatzoglou 2014; Schwartz and Ahas 2006). For instance, Rigby et al. (2008) reported that spring frost events of similar intensity occurred almost symmetrically around the mean date of last spring frost, yet only the later event caused damage, highlighting the threshold-like dependence of plant damage on temperature during budbreak. Therefore, simply counting the number of frost days during a fixed period (e.g., March–May) may not fully capture the risk of spring frost-induced damage across regions with different phenological timings. There is a need to use long-term large-scale phenological data for more accurately assessing the ecological and agricultural impacts of spring frost events.

In North America, cropland is facing increased frequency of spring frost, while cropland in Eurasia is experiencing reduced frequency of spring frost. Currently, research on the risk of spring frost in agricultural regions tends to focus on local areas, which limits in-depth insights into the global risk pattern to some extent (Ma et al. 2019; Nidzgorska-Lencewicz et al. 2024; Vitasse and Rebetez 2018b; Zhong et al. 2007). Our current work overcomes such limitations, by comprehensively assessing the risk of spring frost on cropland in North America and Eurasia from a much more macro perspective. Our findings remind us that in addressing the agricultural risk of spring frost, agricultural regions in North America and Eurasia may require adopting different management strategies. Especially considering the increasing risk of spring frost of cropland in North American, we need to take measures to strengthen the monitoring and early warning capabilities for spring frost in these agricultural regions.

In this work, we defined spring frost events using a 0 °C threshold, commonly referred to as a "soft freeze" (Savage et al. 2025). The "soft freeze" threshold may not fully capture the biological severity of spring frost damage. In agricultural and ecological research, a stricter definition, referred to as a "hard freeze" (approximately −2.2 °C), is also often adopted because it is closely associated with irreversible cellular injury, particularly during sensitive stages such as budburst, flowering, or leaf expansion (Smith 2019; Savage et al. 2025). Therefore, the choice of spring frost threshold can lead to different interpretations of spring frost risk and its ecological or agricultural consequences. In future research, there is a need to investigate the impact of spring frost defined as hard freeze for specific crops.

In this research, we have utilized two different datasets to mutually verify the conclusions. Through analysis and comparison, we have found that the conclusions drawn from the two datasets are generally consistent, but there are certain differences in some details. The existence of differences between different datasets is a common phenomenon, and numerous studies have already explored this issue (Cheng et al. 2021; Escorihuela & Quintana-Seguí 2016). In this study, the major difference between the two datasets lies in their temporal and spatial resolution, which may have led to differences in data processing and analysis, ultimately affecting the final results. Despite these differences, the consistency of the basic conclusions drawn from the two datasets still enhance the reliability of our research results.

5 Conclusions

The present research was an attempt to study the changes in spring frost patterns in the Northern Hemisphere by using historical global temperature data. Our analysis has revealed that the percentage of regions with increased spring frost is increasing in North America, whereas it is decreasing in Eurasia. Further to study the impact of spring frost on cropland, we have found that the frequency of cropland experiencing spring frost is increasing in North America, while it is decreasing in Eurasia. It is worth mentioning that the conclusions we have drawn using two datasets are consistent, further enhancing the reliability of our research results. Our current study suggests that given the increasing risk of spring frost in cropland in North America, agricultural regions in North America and Eurasia may need to adopt different management strategies.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s00704-025-05988-w.

Acknowledgements The authors extend their gratitude to Dr. Carol K. Augspurger from the University of Illinois at Urbana-Champaign for reviewing an earlier version of this manuscript and offering valuable insights. They also sincerely thank Dr. Deepak Ray from the University of Minnesota for his thoughtful review and comments on the manuscript.

Author contributions Wei Guo performed the analyses and wrote the first version of the manuscript. Chuhan Lu, Ping Xia, Lijiang Fu, Hao Tang and Jian Chen assisted with data processing. Govindjee Govindjee, Li Song, and Jinglu Tan helped with the discussions of the results and the revision of the manuscript. Zhenyu Xu helped in interpreting the results. Ya Guo contributed to designing the study, interpreting the results, seeking funding, and in manuscript revisions.

Funding This project is partially supported by National Natural Science Foundation of China (No: 51961125102, 31771680), Jiangsu Agricultural Science and Technology Innovation Fund (SCX (22)3669), and the 111 Project (B23008).

Data availability No datasets were generated or analysed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

Allevato E, Saulino L, Cesarano G, Chirico GB (2019) Canopy damage by spring frost in European Beech along the Apennines: effect of latitude, altitude and aspect. Remote Sens Environ 225:431–440

Augspurger CK (2013) Reconstructing patterns of temperature, phenology, and frost damage over 124 years: spring damage risk is increasing. Ecology 94:41–50

Bascietto M, Bajocco S, Mazzenga F, Matteucci G (2018) Assessing spring frost effects on Beech forests in central Apennines from remotely-sensed data. Agric For Meteorol 248:240–250

Cannell MGR (1985) Analysis of risks of frost damage to forest trees in Britain. Crop Physiology of Forest Trees. Helsinki University Press, pp 153–166

Cannell GR, Smith R (1986) Climatic warming, spring budburst and forest damage on trees. J Appl Ecol 23:177

Cheng Y, Huang M, Zhu B, Bisht G, Zhou T (2021) Validation of the community land model version 5 over the contiguous United States (CONUS) using in situ and remote sensing data sets. J Geophys Res Atmos 126(5):e2020JD033539

Clayton S, Karazsia BT (2020) Development and validation of a measure of climate change anxiety. J Environ Psychol 16:101434

Cowherd M, Leung LR, Girotto M (2023) Evolution of global snow drought characteristics from 1850 to 2100. Environ Res Lett 18:064043

Crimp SJ, Zheng B, Khimashia N, Gobbett DL, Chapman S, Howden M (2016) Recent changes in Southern Australian frost occurrence: implications for wheat production risk. Crop Pasture Sci 67:801–811

Dunn RJH, Lisa VA, Markus GD, Zhang X, Bador (2020) M. Development of an updated global land in Situ-Based data set of temperature and precipitation extremes: HadEX3. J Geophys Research: Atmospheres 125(16):e2019JD032263

Dunn RJH, Donat MG, Alexander LV (2022) Comparing extremes indices in recent observational and reanalysis products. Front Clim 4:989505

Eccel E, Rea R, Caffarra A, Crisci A (2009) Risk of spring frost to Apple production under future climate scenarios: the role of phenological acclimation. Int J Biometeorol 53:273–286

Eekhout J, Vente J (2019) Assessing the effectiveness of sustainable land management for large-scale climate change adaptation. Sci Total Environ 654(1):85–93

Escorihuela M, Quintana-Seguí P (2016) Comparison of remote sensing and simulated soil moisture datasets in mediterranean landscapes. Remote Sens Environ 180:99–114

Giorgi F (2019) Thirty years off regional climate modeling: where are we and where are we going next? J Geophys Res Atmos 124(11):5969–5723

Hänninen H (2006) Climate. Warming and the risk of frost damage to boreal forest trees: identification of critical ecophysiological traits. Tree Physiol 26(7):889–898

Hawkins E, Sutton R (2012) Time of emergence of climate signals. Geophys Res Lett 30:L01702

Hoffmann H, Rath T (2013) Future bloom and blossom frost risk for *Malus domestica* considering climate model and impact model uncertainties. PLoS One 8:e75033

Holman JD, Schlegel AJ, Thompson CR (2011) Influence of precipitation temperature, and 56 years on winter wheat yields in Western Kansas. Crop Manag 4:1–15

Hong Q (1999) Spatial pattern of vascular plant diversity in North America North of Mexico and its floristic relationship with Eurasia. Ann Bot 83:271–283

Kaukoranta T, Tahvonen R, Ylamaki A (2010) Climatic potential and risks for Apple growing by 2040. Agric Food Sci 19:144–159

Lamichhane JR (2021) Rising risks of late-spring frosts in a changing climate. Nat Clim Chang 11:554–555

Leolini L, Moriondo M, Fila G, Costafreda-Aumedes S (2018) Late spring Frost impacts on future grapevine distribution in Europe. Field Crops Res 222(1):197–208

Lima CZ, Buzan JR, Moore FC, Baldos UL (2021) Heat stress on agricultural workers exacerbates crop impacts of climate change. Environ Res Lett 16:044020

Liu Q, Piao S, Janssens IA (2018) Extension of the growing season increases vegetation exposure to Frost. Nat Commun 9:426

Lu HW, Guan YL, He L, Adhikari H, Pellikka P, Heiskanen J (2020) Patch aggregation trends of the global climate landscape under future global warming scenario. Int J Climatol 40:2674–2685

Ma Q, Huang J, Hänninen H, Berninger F (2019) Divergent trends in the risk of spring Frost damage to trees in Europe with recent warming. Glob Change Biol 25:351–360

Nidzgorska-Lencewicz J, Mąkosza A, Koźmiński C, Michalska B (2024) Potential risk of frost in the growing season in Poland. Agriculture 14:501

Paul KK, Macadam I (2021) Dengue transmission risk in a changing cliamte: Bangladesh is likely to experience a longer dengue fever season in the future. Environ Res Lett 16:114003

Peterson AG, Abatzoglou JT (2014) Observed changes in false springs over the contiguous united States. Geophys Res Lett 41(6):2156–2162

Potapov P, Turubanova S, Hansen MC (2022) Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. Nat Food 3:19–28

Ramankutty N, Foley JA, Norman J, Mcsweeney K (2002) The global distribution of cultivable lands: current patterns and sensitivity to possible climate change. Glob Ecol Biography 11:37–392

Rodell M, Houser PR, Jambor U, Gottschalck J, Mitchell K (2004) The global land data assimilation system. Bull Am Meteorol Soc 85(3):381–394

Sales LP, Parrott L. Lael (2024) The owls are coming: positive effects of climate change in Northern ecosystems depend on grassland protection. Sci Total Environ 907(10):167944

Savage JA, Fakhreddine Q, Vandenheuvel B (2025) Floral freezing tolerance is tied to flowering time in North American woody plant species. Ann Botany 135(1–2):305–316

Schwartz MD, Ahas R (2006) Onset of spring starting earlier across the Northern hemisphere. Glob Change Biol 12:343–351

Sheffield J, Goteti G, Wood EF (2006) Development of a 50-yr high-resolution global dataset of meteorological forcings for land surface modeling. J Clim 19(13):3088–3111

Smith ED (2019) Cold hardiness and options for the freeze protection of Southern highbush blueberry. Agriculture 9(1):9

Tanir T, Yildirim E, Ferreira C, Demir I (2024) Social vulnerability and climate risk assessment for agricultural communities in the United States. Sci Total Environ 908(15):168346

Tilburg AJ, Hudson PF (2022) Extreme weather events and farmer adaptation in Zeeland, the Netherlands: a European climate

change case study from the Rhine delta. Sci Total Environ 844(20):157212
Unterberger C, Brunner L, Nabernegg S, Steininger KW, Sheiner AK (2018) Spring frost risk for regional apple production under a warmer climate. PLoS One 13(7):e0200201
Viana CM, Freire D, Abrantes P, Rocha J, Pereira P (2022) Agricultural land systems importance for supporting food security and sustainable development goals: a systematic review. Sci Total Environ 806(3):15018
Vitasse Y, Rebetez M (2018b) Unprecedented risk of spring frost damage in Switzerland and Germany in 2017. Clim Change 149:233–246
Vitasse Y, Schneider L, Rixen C, Christen D, Rebetez M (2018a) Increase in the risk of exposure of forest andfruit trees to spring frosts at higher elevations in Switzerland over the last four decades. Agricultural and. Forest Meteorology 248:60–69
Wang X, Piao S, Ciais P, Li J, Friedlingstein P, Koven C, Chen A (2011) Spring temperature change and its implication in the change of vegetation growth in North America from 1982 to 2006. Proc Natl Acad Sci U S A 108(4):1240–1245
Xiao L, Liu L, Asseng S, Xia Y, Tang L, Liu B (2018) Estimating spring Frost and its impact on yield across winter wheat in China. Agric for Meteorol 260–261:154–164
Zhang T, Niinemets Ü, Sheffield J, Lichstein JW (2018) Shifts in tree functional composition amplify the response of forest biomass to climate. Nature 556:99–102
Zhong X, Wang D, Zhao P, Yan X, Su C (2007) Occurrence of frost temperature in Huanghuai wheat production zone after winter wheat elongation. Chin Journal Eco-Agriculture 5:003
Zhou Y, Ren G (2012) Change in extreme temperature event frequency over Mainland China, 1961–2008. Clim Res 50(2):125
Zohner C, Mo L, Renner S, Svenning J, Vitasse Y (2020) Late-spring frost between 1959 and 2017 decreased in North America but increased in Europe and Asia. Proc Natl Acad Sci U S A 22:12192–12200