



False springs in the Netherlands: climate change impact assessment with the false spring damage indicator model

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Received: 11 November 2023 / Accepted: 21 April 2024
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Abstract

Strong night frosts in spring have the potential to cause severe damage to fruit trees, causing up to €3.3 billion of damage in Europe in 2017. If temperatures drop below -2.2 °C after the growing season starts, this phenomenon is referred to as a *false spring*. For the Netherlands, the risk of false spring damage increased during the past 70 years, due to the decreasing time between the last strong night frost and the flower budburst. This raises the question of whether this trend will continue under future influences of climate change. To analyse the development of false spring damage risks, we developed the False Spring Damage Indicator (FSDI) model. Applying this model to the Dutch KNMI'14 climate change scenarios for 2050 and 2085 showed a decrease in false spring damage risk. The historical risk for 60% bud damage was reduced to around 40% for the moderate scenario in 2050 and to less than 15% for the severe scenario in 2050 and all scenarios in 2080. False spring damage varied spatially throughout the Netherlands. Currently, more severe damage can be expected in the east, while coastal regions in the north and west are less prone to false spring damage. In the future, this is expected to become more uniform over the Netherlands, as the risk in the east is predicted to decrease strongly, becoming similar to the low damage risk in the coastal regions.

Keywords False spring · Frost damage · Apple trees · Climate change scenarios

Introduction

In 2017, severe frosts occurred across Europe in April and May, causing an estimated €3.3 billion of damage to fruit and wine farmers (Faust and Herbold 2018). This

frost period happened after a relatively warm period in February and March, which caused earlier flowering of horticultural crops, like grape vines and fruit trees. This early flowering, followed by the late, strong frost, caused severe leaf damage and loss in flower tissue (Chamberlain et al. 2019). Generally, a frost event with a temperature of less than -2.2 °C after the buds of a plant have burst is referred to as a false spring (Martinuzzi et al. 2019; Marino et al. 2011). False springs often take place during April and May, when night frost occurs unusually late in the spring season. False springs usually occur in conjunction with abnormally early periods of high temperatures from January to March, which accelerate bud development. Temperature variability is therefore an important factor in false springs (Chmielewski and Rötzer 2001). Part of the temperature variability in Central European springs can be explained by the North Atlantic Oscillation (NAO), an index indicating the strength of the westward atmospheric circulation. The NAO may therefore be a strong predictor for the dynamics of winter dormancy and spring phenology in Europe (D'Odorico et al. 2002;

Communicated by George Zittis

Joep Bosdijk, Vincent S. de Feiter, Annika Gaiser, Thijs Smink and Gudrun Thorkelsdottir contributed equally to this work.

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Chamberlain et al. 2021). False springs are considered an important limiting factor in plant development (Chamberlain et al. 2021), making it relevant to assess their causes, their related damage, and how their occurrence will change in the future. In the context of this study, we will focus on false springs affecting flower buds in the Netherlands since these buds have a direct and strong impact on fruit production.

For plants, temperature determines the development of the phenological stages, thus influencing flower budburst. The start of the growing season is determined by chilling temperatures in winter, which are required to break bud dormancy. These chilling requirements avoid leaf emergence and flower budburst in case of short warm periods in winter (Chamberlain and Wolkovich 2021; Flynn and Wolkovich 2018). When the growing season starts, the need for cold temperatures switches to a need for high temperatures to promote plant growth (Chuine et al. 2016; Flynn and Wolkovich 2018). The specific phenology stage from budburst to full bloom is dependent on the temperature-dependent number of Growing-Degree-Hours (GDH) (Anderson et al. 1986). The spring phenology of many species also appears to be responding to photoperiod (Flynn and Wolkovich 2018), but this factor does not seem very influential in apples. In this study, we only base our assessment on temperature, as has commonly been done in earlier studies.

With climate change, average temperatures during spring will increase, causing plants to develop their buds faster while decreasing the chance of frosts below -2.2 °C occurring. Buds in more advanced development stages are more susceptible to being damaged during frost events. However, the lower risk of strong frosts occurring counteracts this potential increase in false spring damage. Eventually, the balance of these effects determines whether the risk of a false spring increases or decreases. Richardson et al. (2018) suggest that plants responding mostly to temperature, like apple trees, will be at higher risk of false springs due to the increase in temperature. However, others have shown that within Europe the effects of climate change on false spring risk will vary (Chmielewski et al. 2018; Meier et al. 2018; Vitasse and Rebetez 2018). Ma et al. (2019) expect an increase in severity and occurrences in both low-lying maritime and coastal climates in Europe. Furthermore, Pflieger et al. (2019) and Zhu et al. (2019) expect higher frost damage risk with global warming for apple trees (in particular *Malus domestica* Borkh.) in Germany (Pflieger et al. 2019) and agricultural systems in China, specifically (Zhu et al. 2019). In contrast, Allstadt et al. (2015) conclude that no general predictions can be made, as the change in risk will vary spatially and result for some areas in increased and for other areas in decreased false spring damage risks. Detailed analyses of spatial patterns in false spring damage, which

may differentiate, for instance between coastal and inland areas, are still lacking.

Horticultural farming, especially apple production, is an important sector within the Dutch economy. In 2021, the Netherlands had a total production of 245,000 tons of apples (Fruit Logistica and Fruitnet 2022). Therefore, it is crucial to understand how the risk of a false spring will change for apple trees due to climate change. A better understanding of false spring risks will help to assess the need for adaptation measures in the horticultural farming sector in the future. Appropriate risk mitigation strategies will require a nuanced understanding not only of temporal trends in false spring risks but also of the spatial variation, for instance, in differences between coastal and inland areas.

In this study, we aim to assess the effect of climate change on false springs in the Netherlands by expanding the phenology model PhenoFlex (Luedeling et al. 2021) into the False Spring Damage Indicator (FSDI) model. We use the FSDI model to classify and explore trends of false springs in the past and to generate a forecast of future false spring damage. We feed the model with meteorological data and climate change projections for weather stations throughout the Netherlands. This allows us to explore regional differences in false spring risk across the Netherlands. We hypothesise that the risk of false springs will keep increasing in the future, especially in the inland areas of the Netherlands, where spring temperatures will rise the most compared to coastal regions, and night frosts are expected to remain common.

Methods and approaches

False Spring Damage Indicator model

The False Spring Damage Indicator (FSDI) model is based on the PhenoFlex model (Luedeling 2022). PhenoFlex models the spring phenology of primarily fruit and nut trees, using a dynamic modelling approach for chill accumulation and a Growing-Degree-Hours (GDH) model for heat accumulation (Luedeling et al. 2021). The GDH approach is, when calibrated properly, the most reliable phenology modelling approach for fruit trees that is currently available (Drepper et al. 2020, 2022). PhenoFlex is one of the most accurate models for predicting bloom dates of temperate fruit trees, outperforming several other models (Luedeling et al. 2021). A detailed explanation of the model and corresponding *chillR* R package is provided by Luedeling (2022) and Luedeling et al. (2021).

We expanded the functionalities of the PhenoFlex model with the FSDI function to estimate the amount of false spring damage per year. We calculated these estimates for the past, using historical data, and for the future, using different climate change scenarios. The FSDI function defines

six phenological stages from budburst to blooming: silver tip, green tip, half-inch green, tight cluster, full pink, and full bloom (Online Resource Fig. S.3). The timing of these stages is dependent on the start of heat accumulation and the total accumulated heat (measured in GDH as calculated by the PhenoFlex model). The transitions between the phenological stages are defined as stage-specific shares of the total required heat accumulation between budburst and flowering. The required heat accumulation to transition into the next stage was taken from Anderson et al. (1986). Since the PhenoFlex model is based on the GDH model, these boundaries are an accurate representation of the phenological stages within the model (Luedeling et al. 2021).

For each phenological stage, the critical temperature for frost damage to occur was defined according to MSU (2021) and Longstroth (2021). The combination of temperature and the current phenological stage can be used to calculate the total FSDI score per year. We calculated this score using Eq. (1). Subtracting the score of the final time step from the start score of 100 results in the false spring damage for each year, with 0% being no damage and 100% being complete damage.

$$\text{Score}_{(t+1)} = \text{Score}_{(t)} \cdot D_{(t)} \quad (1)$$

$$\text{FSDI} = 100 - \text{Score}_{(t=t_{\max})}$$

The time step t is given in hours, $\text{Score}_{(t=0)} = 100$, and $D_{(t)}$ is the fraction of buds that is expected to survive, which is dependent on the phenological stage and the temperature T . The expected damage is divided into four categories (MSU 2021; Longstroth 2021):

- damage category 0 (no damage): $D = 1$
- damage category 1 (first damage): $D = 0.99$
- damage category 2 (10% kill): $D = 0.9$
- damage category 3 (90% kill): $D = 0.1$

Damage category 1 is equal to the lowest temperature endured for 30 min without damage (referred to as “old temp” by Longstroth (2021)). Damage categories 2 and 3 are the temperatures at which 10% and 90% of buds are killed, respectively (Ballard and Proebsting 1972). A detailed explanation of the FSDI model setup and functionality is given in the Online Resource Section S.4.

Data sources and handling

The study was performed for the Netherlands, which is characterised by a temperate maritime climate, a Cfb-climate in the Köppen-Geiger classification. According to Beck et al. (2018), the south of the Netherlands might transition to a Cfa climate by the end of the twenty-first century. For the

analysis and building of the FSDI model (FSDI model), three main data sources were used: phenology data, historical temperature data, and climate change scenario temperature data.

Phenology data

The phenology data was provided by Nature Today/Natuur Kalender (Nature Today 2022) (not publicly available). It includes the first date of flowering for different apple varieties, covering the period of 1958–2015. The majority of the observations originated from five locations in the Netherlands: Randwijk, Geldermalsen, Kesteren, Wilhelminadorp, and Numansdorp (Online Resource Fig. S.1). The remaining observations were submitted by volunteer observers of the Dutch phenological network, De Natuur Kalender, from different places in the Netherlands. We selected the four apple varieties with the highest data availability for the model analysis: Boskoop, Cox, Golden Delicious, and James Grieve. The apple variety with the best model performance was selected to perform the main analysis, as this allows the most meaningful analysis of false springs.

For the FSDI model (FSDI model), we used only a part of this phenology data, to be representative of the meteorological station De Bilt, which is seen as the meteorology centre of the Netherlands (Online Resource Fig. S.1). We filtered the phenology data to an area where the average temperatures are similar to the temperature of De Bilt, using the spatial climatological average maximum and average minimum temperature observations in spring from the Royal Netherlands Meteorological Institute (KNMI) (KNMI, nda). We used the remaining phenology data, which fall outside of the average temperature area, to assess the model performance for regions outside of the filtered area (see Model performance).

Lastly, we defined the growing season for apple trees in the Netherlands using the phenological data and the PhenoFlex model (Luedeling 2022). The growing season is defined as starting on the date the chilling requirement of the plant is met and ending when the plant has fully flowered. Based on the data and initial model results, the start of the growing season was defined on the 1st of January, and the end of the growing season was defined on the 31st of May.

Historical temperature data

We used publicly available hourly temperature data from 34 meteorological stations of the KNMI (KNMI, ndb) (Online Resource Section S.8). This hourly data is required for the PhenoFlex and FSDI models, as both models operate at an hourly time step. For the majority of the stations, the data is available from 1951 up until the present day. Out of this

data, we selected the time frame for which phenology data is available.

Temperature data for climate change scenarios

We performed a scenario analysis to assess how false spring occurrence and damage might develop in a future climate. As scenarios, we used four KNMI'14 climate change scenarios: G_L , G_H , W_L , and W_H for the years 2050 and 2085 (KNMI 2014; van den Hurk et al. 2014). These scenarios are publicly available and are a translation of the global RCP 4.5 (G-scenario) and RCP 8.5 (W-scenario) scenarios of the Intergovernmental Panel on Climate Change (IPCC) to the geographical context of the Netherlands. The subscripts L and H describe different changes in airflow patterns, where L represents low changes and H represents high changes in airflow patterns. A more detailed explanation of the scenarios is given by KNMI (2015).

For the scenarios, the KNMI uses daily average, minimum, and maximum temperatures for a reference period from 1981 to 2010. This 30-year time frame is transformed for the future climate scenarios of the years 2050 and 2085. As hourly data was required, a diurnal temperature curve was estimated using the R package *chillR*, which applies sine-shaped daytime warming and logarithmic nighttime cooling. The transition between day and night depends on the location-specific sunrise and sunset times, and the duration of the transition is related to the day length (Luedeling 2022).

Model performance

The model performance was assessed by comparing the predicted to the observed bloom dates with the following metrics: Root Mean Square Error between observation and prediction (RMSEP); Ratio of Performance to Interquartile Distance (RPIQ) between the 25th and 75th percentile (Luedeling 2022); and the index of agreement (IOA) (Willmott 1982). Large RPIQ values indicate a good model fit, while values below 1 suggest a strong deviation from the observations. The IOA describes the average relative error, with values close to 1 indicating good model accuracy (Willmott 1982).

This validation was done for the meteorological station De Bilt with the Betuwe data and for the meteorological station Rotterdam with the coastal phenological data for the four apple varieties mentioned in the “Data sources and handling” section. These meteorological stations were selected based on their geographical location and the long period measured. To parameterise the model, we used observational data from all odd years of the Betuwe. The even years were used for validation. For the coastal climate, we validated the Betuwe-parameterised model against the coastal phenology data to analyse the implications of using the model in a region it was not parameterised for (Model performance).

Risk assessment

To investigate spatial and temporal developments of the risk of false springs in the Netherlands in recent decades, we used the historical KNMI temperature data as input for the FSDI model.

Since the occurrence of false springs strongly relies on the bloom date, we visualised a possible trend of the bloom date over the past decades. We subsequently compared this trend to the trend of the last day with potentially damage-inducing night frost (where an hourly minimum temperature < -2.2 °C was measured), allowing for determining whether the likelihood of a false spring occurrence decreases (trends diverge) or increases (trends converge). To put these trends into context for the whole of the Netherlands, we used 2D Ordinary Kriging spatial interpolation with an exponential variogram model to develop a geographical representation of the average bloom date and last date of strong frost (Online Resource Section S.7).

To further assess the risk of false spring occurrence during the past 50 years (hereafter referred to as the historical risk), we calculated the expected damage for each year with the FSDI model for 34 KNMI meteorological stations, scattered over the Netherlands. From this data, we assessed the historical risk of false spring damage in the range of the 0th to 100th percentile with increments of 0.5. This is visualised in a geographical representation of the 85th percentile (15% risk) similar to the last date of frost and bloom date.

To investigate the future development of false spring occurrences, we analysed the model output for the four future KNMI'14 climate scenarios, as mentioned in the “Data sources and handling” section. We used a similar approach to the risk assessment for the historic climate. However, from the initial 34 KNMI-stations, only 24 stations had data available for future climate scenarios. To analyse differences between the scenarios, the maximum and average false spring damage over the Netherlands over the respective time frames for the scenarios were calculated and compared to each other.

Results and discussion

Model performance

Table 1 shows the model performance for two regions of the Netherlands in which most apple trees are cultivated: De Bilt for the Betuwe (inland location) and Rotterdam for Zeeland (coastal climate). The RMSEPs of the different apple varieties ranged between 3.8 and 7.2 days (Table 1). The RMSEP of Boskoop is with 3.8 days comparable with the RMSEP described by Luedeling et al. (2021) for the PhenoFlex model. The comparably higher RMSEP of 5.07

Table 1 Root Mean Square Error Predictions (RMSEP), Ratio of Performance to Interquartile Distance (RPIQ), and Index Of Agreement (IOA) for the simulated bloom date. For Boskoop under the coastal climate, no statistics were calculated due to data scarcity

Apple varieties	Betuwe climate			Coastal climate		
	RMSEP [days]	RPIQ [-]	IOA [-]	RMSEP [days]	RPIQ [-]	IOA [-]
Boskoop	3.81	3.67	0.96	n.a	n.a	n.a
Cox	5.66	2.29	0.90	5.04	1.64	0.92
Golden Delicious	5.27	2.89	0.93	6.28	1.27	0.90
James Grieve	5.07	2.76	0.92	7.02	1.28	0.84

(Betuwe) and 7.02 (coast) for James Grieve can be explained by one substantial outlier with one unusually early bloom date observation. This outlier was not predicted correctly by the model, both for De Bilt and Rotterdam. The IOA showed good results, being for all apple varieties of the Betuwe climate at 0.9 or higher, with the best performance for Boskoop with an IOA of 0.96. For the coastal climate, the IOA was slightly lower with values between 0.84 and 0.92 (Table 1). The RPIQ indicates a similar model performance for the Betuwe climate compared to the coastal climate, with the RPIQ of the coast being smaller (1.27–1.64) than for the Betuwe (2.29–3.67) (Table 1).

Risk assessment

Historical trends

For each year, the damage simulated by the FSDI model is displayed (Fig. 1a), revealing whether a false spring occurred, as well as the intensity of such events. When the simulated damage of a year is reported to be > 90%, we regard it as a severe false spring, in which the majority of the apple tree buds or flowers are damaged or lost. According

to this definition, the years 1976, 1981, 1991, and 2022 can be regarded as severe false spring years (Fig. 1a). Over the observed years, no clear temporal trends or patterns of false spring occurrences were observed. However, similar meteorological patterns were observed during the unfolding of false spring events by comparing the NAO for non-false spring and false spring years (elaboration can be found in Online Resource Section S.6). The 12 weeks preceding the false spring events identified with the FSDI model had a significantly higher NAO (average of 0.35), indicating stronger than average westerly flow transporting milder air to the Netherlands. Consequently, the average temperature was significantly higher (average anomaly + 0.9 °C in De Bilt). This is the period in which a surplus of GDH is accumulated. During the days leading up to a false spring, NAO becomes negative, a ridge of high pressure builds over the Atlantic Ocean, and cold air advection brings cold air from the north to the Netherlands. The period between 2 days before and 2 days after the false spring event had a significantly lower NAO (average of - 0.24), indicating a sudden breakdown of westerly flow. The temperatures were significantly lower (average anomaly - 3.2 °C in De Bilt). Consequently, the cold air led to night frost if calm winds and clear skies were

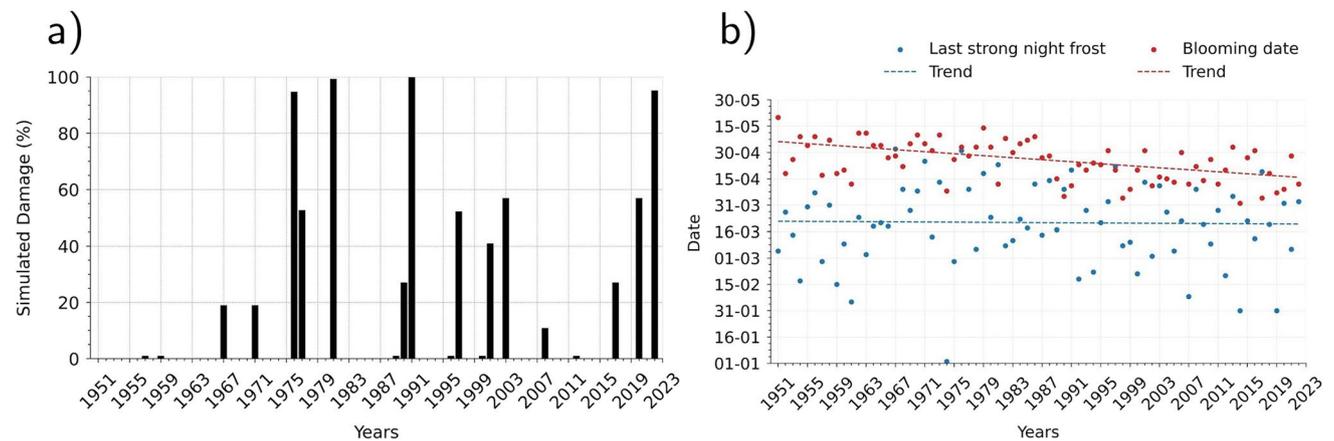


Fig. 1 Yearly simulated damage for De Bilt. **a)** Damage in percentage per year for 1951–2022. **b)** Last date of strong frost reported in spring by the KNMI (< -2.2 °C, blue) and the first day of blooming (red)

and their best-fitted trend lines calculated by the FSDI model for De Bilt for Boskoop

present. False springs therefore seem to strongly depend on seasonal and interseasonal variability of the NAO.

To further understand how false spring years occur, the modelled bloom date for Boskoop apples over the years 1951–2022 was plotted alongside the date of the last strong frost (< -2.2 °C) (Fig. 1b). Over time, the bloom date of Boskoop apple trees has shifted earlier in the year (Fig. 1b). We used the Mann–Kendall test to investigate the possibility of trends in the two variables. The bloom dates showed a trend towards occurring earlier in the year (p -value = $1.88e-5$ and $\tau = -0.34$), with an average shift of one day every three years. Over the last 70 years, the total shift has amounted to up to 3 weeks. In contrast, the Mann–Kendall test did not show a trend for the last date of strong night frost (p -value = 0.91 and $\tau = -0.008$). Since the bloom date shifts earlier in the year and the last frost date stays consistent, the time between the two dates is reduced (Fig. 1b). Consequently, the plant is further developed when the strong night frost occurs and therefore experiences a higher risk of severe false spring damage (Online Resource Fig. S.3). However, it needs to be noted that, while the timing of the last frost remained stationary in our analysis, the number of frost events between the 1st of January and the 31st of May has been decreasing in recent years. Ligtoet et al. (2013) reported that around 1950, the average number of frost days in the Netherlands (here defined as < -5 °C) was 75 days per year, whereas by 2013, this number had dropped to 54 days per year. In our analysis, similar results were obtained at De Bilt station, where days with night frost of < -2.2 °C showed a decreasing trend from the year 1951 until 2022 according to a Mann–Kendall test (p -value = 0.036 and $\tau = -0.169$).

When only comparing the FSDI between the years (Fig. 1a), no trend or pattern was observed, while a shift was spotted in blooming dates timeseries (Fig. 1b). This mismatch between the FSDI and the bloom date trends

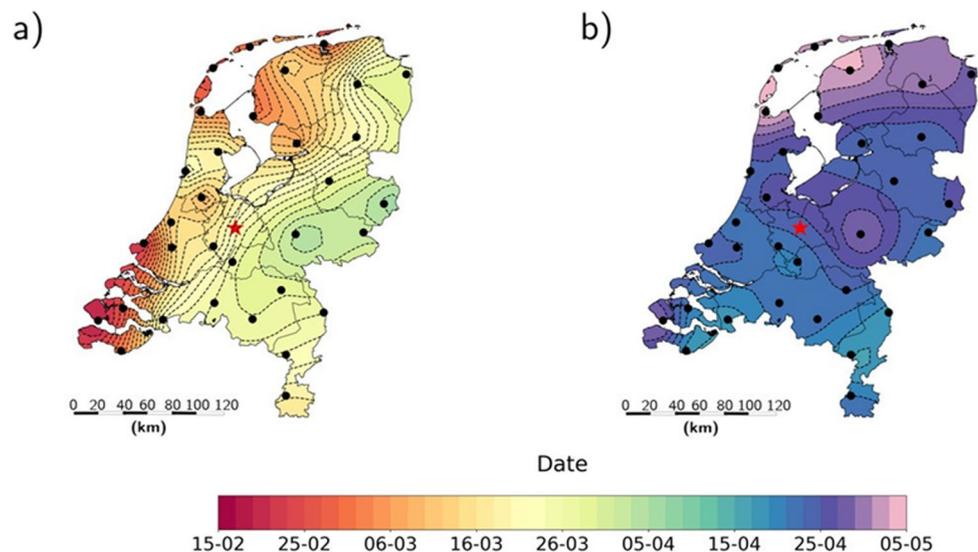
can be explained by annual variability, despite the overall trend of bloom dates showing a shift towards earlier in the year. Therefore, by only looking into whether a false spring occurred in a year, as is done in Fig. 1a, the overall development of false springs is not fully captured. Here, the decreasing number of frost events, which were addressed in the previous paragraph, also contributes to the absence of a trend. While the risk of more severe frost damage increases due to the advancing bloom date, the decrease in frost dates counteracts this trend. Therefore, to assess a trend in the historical development of false springs, it is necessary to look at the development of the dates over a longer time.

Spatial representation

To assess spatial differences in the risk of false spring damage in the Netherlands, we analysed maps of the average bloom date and the last date of severe frost for 1951–2022 (Fig. 2). The last day of a frost event below -2.2 °C in the Netherlands ranged from the middle of February until the beginning of April (Fig. 2a). The map shows an east–west gradient, with differences of up to 47 days between the country’s east and west. This gradient can be best explained by the inflow of warmer and more humid air from the North Sea in the west combined with (strong) longwave radiative cooling during calm and clear nights in the east and southeast. Thus, mainly the presence of the North Sea leads to earlier last dates of frost in the coastal regions.

A gradual spatial gradient was detected for the bloom dates, which ranged from mid-April in the south to early May in the north (Fig. 2b). The difference between the south and the north of the country was up to 20 days. The earlier bloom date in the country’s south compared to the north can be explained by higher average maximum temperatures during spring in response to the inflow of warm

Fig. 2 Spatial distribution over the Netherlands of **a)** the average last date of strong frost in spring and **b)** the average first bloom date of the year for 1951–2022. The black markers represent the meteorological stations of the KNMI. The red star indicates the De Bilt station



air from the south or southeast of Europe. This inflow causes an earlier start of the growing season and an earlier budburst, increasing the vulnerability to frost damage. The combination of these early bloom dates and the late last day of frost results in a higher likelihood of false spring events in the south and east of the Netherlands.

The spatial differences in false spring damage risk become more clearer when combining the average bloom date and the average last date of severe frost into a country-wide risk assessment by calculating the risk for 34 meteorological stations of the KNMI distributed over the Netherlands (Fig. 3). As indicated before, the east of the country has the highest risk of false spring damage (Fig. 3b). The northwest and southwest show a low risk for false spring damage at the 85% percentile. To assess whether the bloom or frost date has a higher influence on the spatial differences in FSDI risk, their spatial trends can be analysed. The last date of strong frost varies about 7 weeks with an east–west gradient within the Netherlands, whereas the first bloom date varies about 3 weeks with a north–south gradient. Thus, spatially the most important factor in determining false spring risk is the last date of strong frost in the Netherlands. A detailed analysis of more localised differences, e.g., for dunes and more urban areas, can be found in the Online Resource Section S.1.

Future false spring risk

As seen in the historical trends, the risk of false springs changes over time. To estimate the false spring risk with climate change, we performed a risk assessment for the four

KNMI’ 14 climate scenarios for 2050 and 2085, similar to the analysis for the historical data (Fig. 4b). We also investigated the average and maximum damage for each scenario compared to the historical average (Fig. 4a). For the following quantitative comparison between past and future risks, it should be considered that the past risk is derived from observations, while the future risk is based on the KNMI’ 14 climate scenarios. In case of any inaccuracies in the climate scenarios, slightly varying values in the FSDI results can be expected. However, the qualitative differences and trends are expected to remain visible. We observed a trend of decreasing false spring risk in the future and a lower risk under the W_L and W_H scenario compared to G_L and G_H (Fig. 4a).

For the scenarios G_L and G_H , the risk of false spring damage is around 50% for 2050 and 35% for 2085. For the W_L and W_H scenarios, the likelihood of false spring damage is considerably lower, at around 20% for 2050 and 5% for 2085 (Fig. 4b). It needs to be noted that these likelihoods are an indication of the first occurrence of false spring damage, corresponding to an FSDI of around 1%. The chance of more severe false spring damage is considerably lower, shown by an initially slow increase of occurrence per simulated damage (Fig. 4b). Only for the G_L and G_H scenario of 2050 damage of more than 15% can be expected with a chance of 10% (G_L) and 8% (G_H). For the other scenarios, the expected damage is less than 15%, or even less than 5% for W_L and W_H in 2085 (Fig. 4b). This behaviour differs from the historical trend, which shows a similar chance of the first indications of false spring damage as G_L and G_H for 2050. However, for the historical average, the chance of

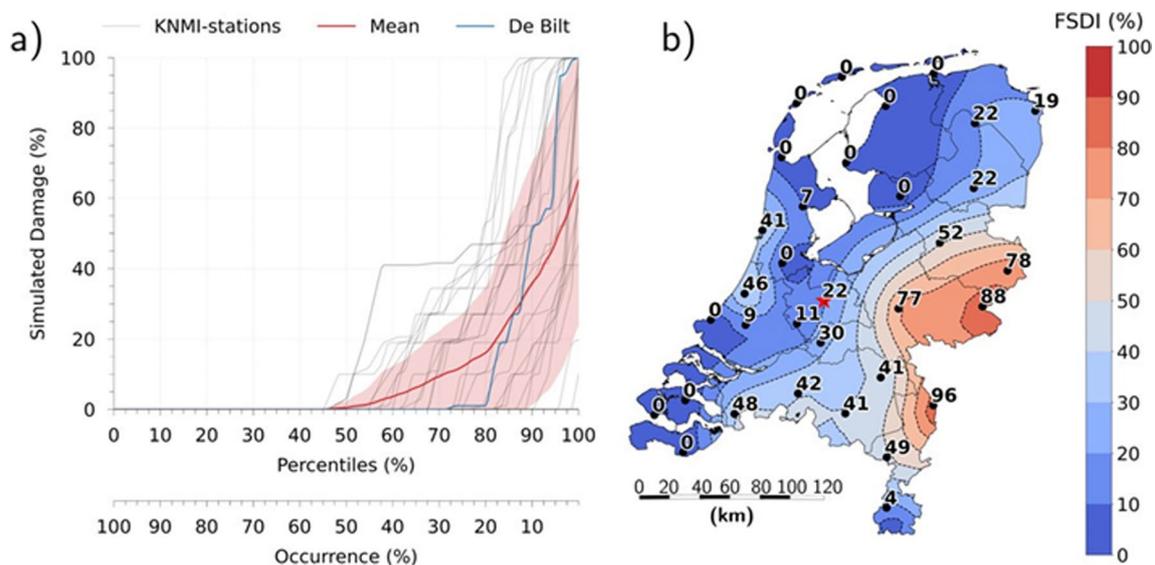


Fig. 3 Historical average of false spring-related frost damage in the Netherlands. **a)** Risk for false spring damage for each 5% percentile for 34 meteorological stations (grey lines), highlighting De Bilt (blue line) and the average risk over the whole country (red line) with the

standard deviation (shaded). **b)** Spatial distribution of the 85% percentile (15% risk) results over the Netherlands. The red star marks the meteorological station in De Bilt and the black markers the remaining stations

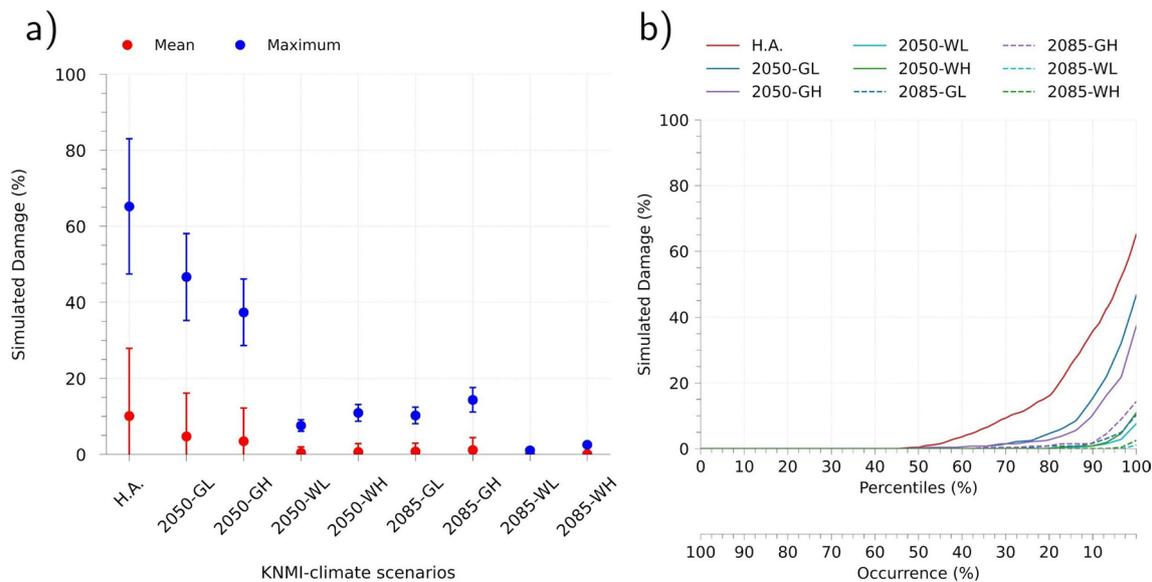


Fig. 4 Future risk of false spring damage for the four KNMI climate scenarios G_L , G_H , W_L , and W_H for the climate around 2050 and 2085. **a)** The average maximum (blue) and mean (red) false spring damage over the Netherlands over the respective time frames for the historic

(H.A.) and future climate scenarios, with the standard deviation as error bars. **b)** The historical average and future mean risk (and occurrences) over the Netherlands per 5% percentile for each scenario, for the years 2050 and 2085

more severe damage increases faster, with a likelihood of 20% for an FSDI greater than 15% (Fig. 4b). So, compared to the historical trend, the risk of higher FSDI values is considerably lower or even non-existent under future climate change scenarios.

With the decreasing risk of false spring damage in general, the magnitude of the expected damage changes (Fig. 4a). The mean expected damage decreases from 10% for the historical average to 0–5% for the climate change scenarios. While this seems negligible, the possible maximum damage is still considerable for the G_L and G_H scenario for 2050, with 38–48% expected damage. For G_L and G_H in 2085 and W_L and W_H in 2050, the expected maximum damage ranges between 9 and 15%. For W_L and W_H in 2085, the maximum expected damage is minimal, at less than 5%. It is interesting to note that the relation between G_L and G_H changes from 2050, with G_L indicating greater damage, to 2085, with G_H indicating higher damage. For W in both years, the H scenario shows higher damage. The decrease in standard deviation indicates lower spatial differences over the Netherlands with increasing time and for W_L and W_H climate scenarios.

Overall, these future scenarios contrast with the historical trend of an increased risk of false spring damage. This relates to the bloom date and day of the last frost diverging over time for the different climate change scenarios (not shown). Thereby, the last day of frost is expected to occur earlier in the year, resulting in less overlap with the growing

season and therefore a reduced chance of severe false spring damage. Additionally, as was discussed in the “Risk assessment” section, the number of frost nights is expected to decrease with climate change. It is not entirely clear whether this already affected the occurrence of false springs in the historical analysis, as the timing of the day of the last frost stayed constant over the years. With the change of the frost date, this might play an increasing role in the future, reducing the expected risk. As the severity of the future climate scenarios increases, the false spring damage decreases with the decreasing number of frost events. These results suggest that at some point between the current year and 2050, the risk of a false spring may reach a maximum, but then start to decrease again as frost occurrences become rarer. However, since no continuous time series from the past to the future could be analysed, there is some uncertainty as to whether or how this inflection point will occur and how biases in the climate change scenarios may have impacted this result. KNMI (2014) and van den Hurk et al. (2014) mention that a possible systematic bias in the trends in the global climate models used for constructing the KNMI’14 climate change scenarios may influence their output range, but it is unclear how likely such a bias is and what its likely sign may be. Based on this explanation, it may be possible that the described change in the trend of frost days is affected in its timing. However, it seems unlikely that this inflection will not occur at some point.

Uncertainties

In this study, the future development of false springs was completely based on the KNMI'14 climate scenarios. These are based on transforming the hourly temperature of 1980–2010 to represent the temperature in the future. By transforming an existing time period, the day-to-day and hour-to-hour variation causing most of the false spring damage is realistically represented in the modelled future climate. The KNMI'14 scenarios should, therefore, capture some of the possible extreme frost events that lead to false springs (KNMI 2015). However, climate models underestimate extreme weather, including night frost, which can lead to underestimation of the number of false spring occurrences in the future (Unterberger et al. 2018). Additionally, as mentioned before, biases related to the generation of the scenarios based on global climate models may affect the results (KNMI 2014; van den Hurk et al. 2014). Therefore, the accuracy of the FSDI model depends heavily on the accuracy of the climate model used.

Another shortcoming of the model is the absence of variation in phenology characteristics. The susceptibility of buds to a frost event can vary for the following four reasons: (1) varieties of apples can produce buds that vary in their susceptibility to frost events (Ballard and Proebsting 1972). (2) The temperature 24 h prior to the frost event can increase or decrease the susceptibility of buds to frost events (Ballard and Proebsting 1972). (3) The temperature during which the buds and flowers grow can increase or decrease the susceptibility of buds to frost events. Low temperatures during dormancy make buds hardier, while warm temperatures make them more susceptible to frost events (Ballard and Proebsting 1972). (4) Damaging frost events were found to make leaves of maple and birch trees more susceptible to consecutive frost events (Chamberlain and Wolkovich 2021). This may also be the case for apple trees.

Finally, validation of the FSDI model results was not possible due to a lack of reported frost damage. Therefore, the results have to be interpreted with some caution. Furthermore, the FSDI damage index assumes no protection to prevent frost damage. The damage index can, therefore, not be compared to the damage to plants that have been protected from frost events. Farmers usually know a false spring might be coming and will take preventative measures beforehand to protect their apple trees, making it difficult to gather validation data since a farmer would have to leave their apple trees unprotected deliberately. The best possibility of gathering validation data would be at experimental study sites. At the moment, such data is not available. Alternatively, it might be useful to account for a possible damage reduction through preventative measures in the model to give information on the realistically expected damage.

Conclusion

We analysed false springs temporally and spatially for apple trees in the Netherlands. To analyse the future risk of false spring damage with climate change, a false spring damage indicator (FSDI) model was developed. During the past decades, the risk for false spring damage increased due to an earlier bloom date and consistent timing of the last strong night frost. This trend seems to reverse with ongoing climate change, with less damage expected for the more severe climate change scenarios. While in 2050, damage around 40% can still be expected for the less severe scenarios, by 2085, the damage will decrease to less than 15% for all scenarios. For the Netherlands, specifically, more severe damage can currently be expected for regions in the east, with a gradual decrease towards the coastal regions in the west and north. With climate change, this spatial difference is expected to decrease as the damage overall, and especially in the east of the Netherlands, becomes less severe.

These results give interesting insights into the influence of climate change on false springs, which deserve further investigation. Wherever similar phenology and temperature data are available, the FSDI model can be applied to other geographical regions to provide insights into false spring occurrences and risks. Still, results presented in this study can already give insight into false spring behaviour at other locations with similar climatology as the coastal or inland regions of the Netherlands.

The results can be used as a baseline for future research that aims to improve fruit farming and prevent losses due to false spring damage. Such future research should focus on improving the FSDI model by extending its functionality. So far, the FSDI model is solely based on phenology and temperature data. There may be other processes, such as particular local hydrometeorological conditions or differences in varietal susceptibility to frost damage, that may lead to deviations in the outcome. For improving the FSDI model accuracy, identifying and incorporating such influencing conditions and processes would be interesting. Also, advancing knowledge on modelling night frost with climate change might improve the climate change scenarios and, therefore, raise model accuracy. Besides this, gathering data on false spring damage on fruit trees is critical for the validation and further development of the FSDI model. It would be relevant to get data on fruit orchards where no preventative methods are applied, as these can considerably reduce the damage. Bloom observations in orchards where preventative methods have been applied are not suitable for validation of the potential false spring damage. However, it would be interesting to use data with preventative methods to extend the FSDI model with added functionality that predicts the risk of false spring damage in the presence of adaptation measures.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10113-024-02235-2>.

Acknowledgements We would like to thank Dr. ir. Bert van Hove (Wageningen University & Research) for his advice and supervision of this project during the course “Design of Climate Change Adaptation and Mitigation Strategies” followed in 2022 at Wageningen University & Research, which was the origin of this project. Special thanks also go to Dr. ir. Peter Siegmund (KNMI) for supervising the paper writing process. Further, our thanks go to all our reviewers.

Data availability The phenology data was provided by Arnold van Vliet (Natuurkalender.nl) and is not publicly available. The meteorology data can be accessed from the KNMI website: <https://www.daggegevens.knmi.nl/klimatologie/uurgegevens> (historic data); https://www.knmi.nl/nederland-nu/KNMI14_klimaatscenario's/transformatieprogramma (climate change scenarios).

Code availability We are working on making the scripts of the FSDI model publicly available on GitHub.

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