Climate change and the risk of spring frost in agriculture

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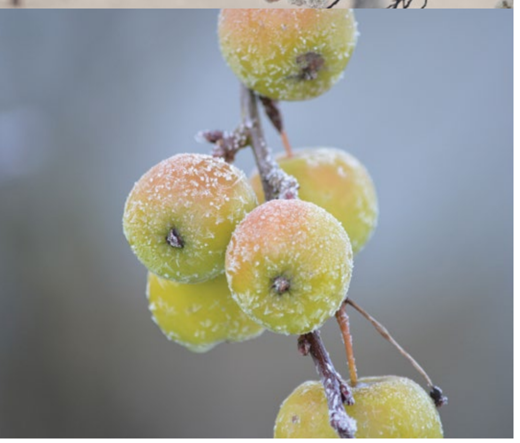
Spring frosts can cause severe losses to the production of fruits and wine grapes. In recent years, European fruit and wine producers have lost a large part of their harvest because of freezing nights during the Spring. Spring frosts are particularly damaging to fruit trees and vineyards after they come into leaf and they are very vulnerable to freezing temperatures.

Warming temperatures move the start of the growing season to an earlier period in the year when freezing temperatures are more likely to occur. To better understand the impact of climate change on fruit and wine production, we examine the impact of changing temperatures on fruit and wine production in Europe. Our study shows that the risk of spring frosts is increasing in vast parts of Europe which will have a significant impact for fruit and wine production.

Climate change moves the spring – and Europe's fruit and wine producers face increasing frost risks



In recent years, Europe's fruit and wine producers were hit by several severe spring frost events. Especially in 2017 and again in 2021, a few nights with freezing temperatures destroyed large parts of the harvest. In France, the worst affected country in 2021, this year's spring frost losses to wine production are expected to exceed EUR 2bn with insured losses estimated to be in a range of EUR 300 to 400m[1].

Frost events[2] are common during winter, and fruit trees and vineyards can generally withstand temperatures below 0°C. However, fruit and wine production becomes increasingly vulnerable to freezing temperatures in spring once the formation of the earliest buds begins. More specifically, agriculture frost losses only result when freezing temperatures (the hazard) occur while plants are in a vulnerable development stage (the exposure). Therefore, a single spring night with minimum temperatures significantly below the freezing point, in areas where the buds had started developing, can destroy the complete yield of fruit growers for that year.

With global warming, Europe's vegetation emerges earlier in the year. Today, the growing season starts about 15 to 20 days earlier than back in the 1980s. While an early growing season start can have some positive impacts — the growing season extends and the risk of water stress in mid-summer months decreases — this also means that the exposure of agricultural production to spring frosts shifts to an earlier period of the year. The vegetation reacts to increasing temperatures with earlier development; to a period when the likelihood of cold nights remains high[3].

Therefore, the harvest of Europe's fruit and wine growers is increasingly at risk of being destroyed during cold nights.

[1] *Numbers based on various media articles (e.g. https://www.theguardian.com/business/2021/sep/07/french-wine-output-frosts-weather) and on estimates of the European Commission (https://ec.europa.eu/info/news/commission-publishes-previsions-eu-wine-production-2021-22-2021-oct-12_en).*

[2] *Defined as the air temperatures falling below 0°C (and therefore independent of the resulting formation of ice needles, which is also called frost).*

[3] *It is likely that also the frequency and severity of cold spring nights are changing, for example due to increasing likelihood of cold air outbreaks (see for example Huang et al. 2021: Northern hemisphere cold air outbreaks are more likely to be severe during weak polar vortex conditions, Nature communications Earth & Environment).*

One swallow does not make a summer

Fruit growers across Europe faced a record-breaking cold spell in early April of this year. Temperatures fell below 0°C in large parts of Europe *(Figure 1)*. Night temperatures were exceptionally low for this time of the year: Minimum temperatures fell 2 – 6 degrees below what has been observed in the first half of April in the long-term average *(Figure 2)*[4]. While this exceptionally cold weather was devastating for the vegetation, and therefore for the harvest of many fruit and wine growers in France, Italy, Croatia, and Spain, the harvest of farmers further north in Europe, where the formation of buds had mostly not yet started, were less strongly affected.

Tmin between April 1 and April 15

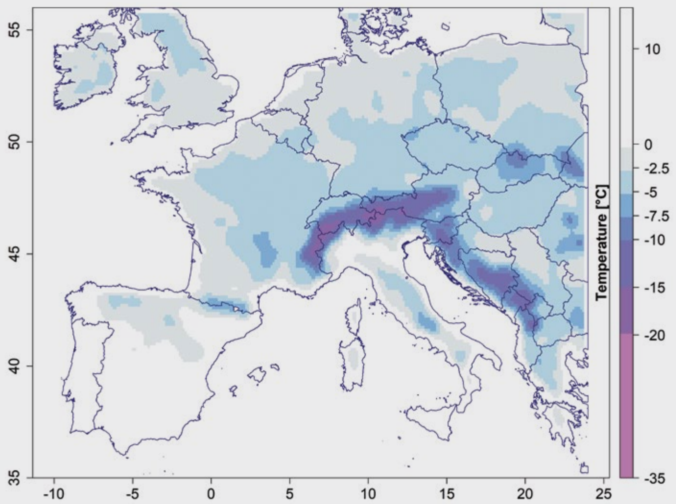


Figure 1: Minimum temperature in the first half of April.

Anomaly — Tmin between April 1 and April 15, 2021

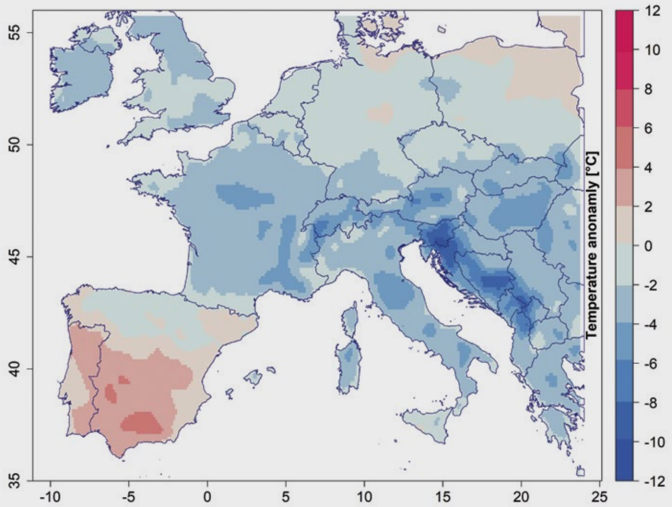


Figure 2: Anomaly of the minimum temperature in 2021 compared to the long-term average minimum temperature in the first half of April (1981-2010). Note that Spain was also affected by an exceptional frost event at the end of March.

In vast regions of Europe, April is the time of the year when the vegetation starts developing. Therefore, the severity of a frost event in April not only depends on the minimum temperature during the frost event alone, but also depends on the timing of the frost (the later it is, the more severe the impact) and on the temperatures in the weeks before the frost (the warmer it is, the worse the impact). Because vegetation emerges only after a certain (crop specific) amount of heat units has accumulated, a frost event in a cold spring is less harmful for farmers than a frost event following a warm period. What made the cold spell of 2021 so harmful in much of Southern Europe, is that it followed a period of particularly high temperatures that had led to an early start of the growing season. In Northern and Central Europe, however, this warmer period was not sufficient for the buds of the plants to start emerging in early April, and many farmers in these regions got away (more or less) loss-free *(see Figure 3 and 4)*.

Average DOY start growing season

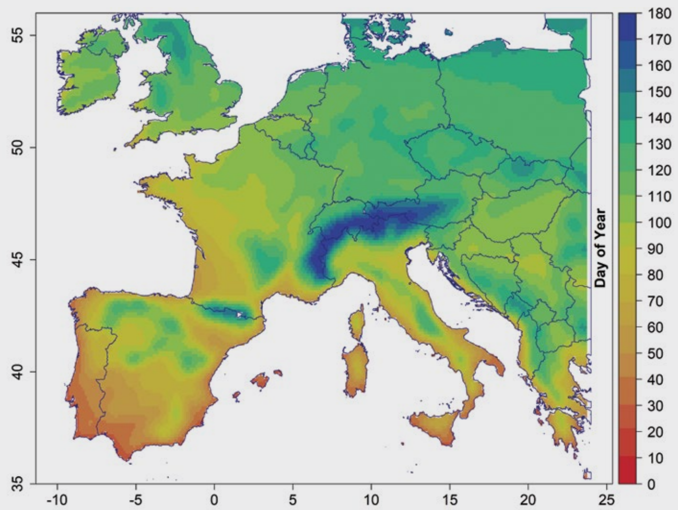


Figure 3: Estimated day of the year when the growing season started in 2021. Note that the most severe frost nights occurred between the 6th and 8th of April, which are the 96th to 98th day of the year (DOY). The frost had the largest impact in those areas, where the growing season had started on DOY 96 (more specifically in France, Italy, Croatia, and some of the more Western parts of Germany).

Anomaly — DOY start growing season, 2021

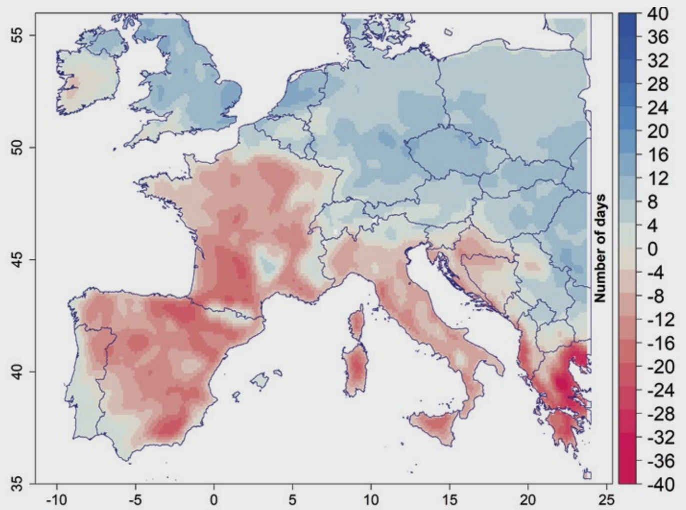


Figure 4: Anomaly of the start of the 2021 growing season compared to the long-term average (1981-2010). The figure shows that the growing season started earlier than usual in Southern Europe while it started later than usual in Northern and Central Europe. This could have happened because it was warmer than usual in March, and therefore warm enough in Southern Europe for the vegetation to start developing. In Northern and Central Europe, this warm spell was not warm enough for the bud formation to start. Afterwards, April and May were relatively cold, delaying the growing season start which had not yet started in March.

Looking back at the last 40 years, frost events in April are not exceptional for large parts of Europe. The North of Spain, the Apennines in Italy, Central and Northern France, along with most of Central Europe, have faced a frost in April between every one and four years *(Figure 5)*. This high return period of spring frosts would be bad news for fruit and wine growers (and insurers) in Europe, yet low temperatures are not the only factor. The phenological stage of the crop during the frost event is also important. This is what *Figure 6* shows and what makes the picture look very different.

It shows that there have been only one or two frost events during the growing season (after the start of bud development, estimated using a generic growing degree day model[5]) in most of Europe. It also presents a pattern of spring frost risk during the growing season in the shape of a line from the Sierra Nevada in Spain going north through central France to the Ruhrgebiet in Germany.

[4] *1981-2010, standard reference period as defined by the World Meteorological Organization (WMO).*
[5] *A growing degree day model describes the day of the year on which the growing season starts by accumulating mean daily temperatures above a certain base temperature until a predefined threshold. For the generic model, we use 5°C as base temperature and a threshold of 200°C.*

A wine tour in Southern France

Beychac-et-Cailleau is a commune just east of Bordeaux in the wine producing region of Gironde *(Figure 7)*. Frost risk is a relevant risk here and Beychac-et-Cailleau provides an illustrative example of a town where frost risk is increasing. As in many other places, we can observe that the climate has been getting warmer. In the 1980s, 200 growing degree days (a proxy for the start of vegetation emergence) were on average reached on the 72nd day of the year (DOY), which means on the 13th of March. In the last decade (2011 – 2020), the vegetation has on average emerged on the 65th day of the year, on the 6th of March *(Figure 8)*[6].

Return perion of frost event in April

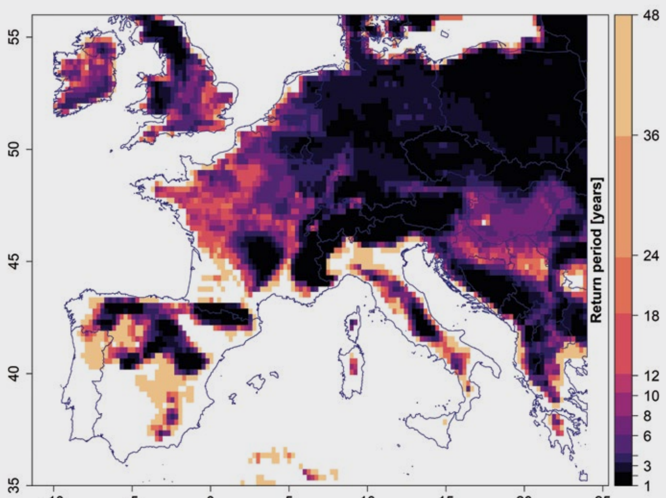


Figure 5: Estimated return period of a frost event in April.

Return perion of a frost event during the growing season

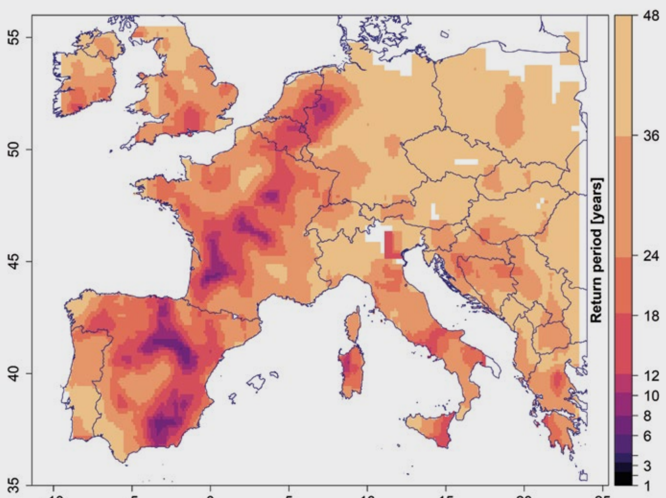


Figure 6: Estimated return period of a frost event during the growing season based on temperature data of the last 43 years. In white areas, the data did not contain a frost event.

Average DOY start growing season

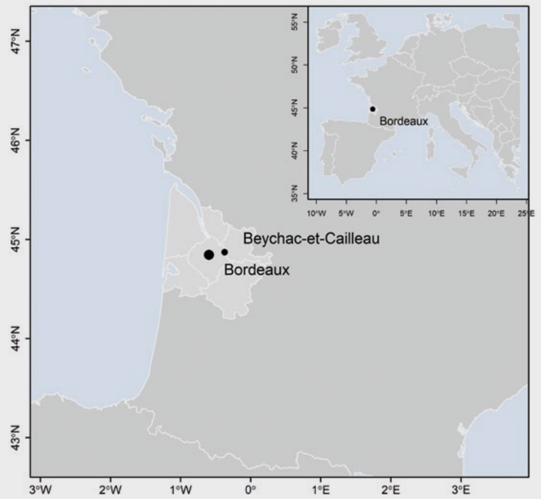


Figure 7: Location of the commune Beychac-et-Cailleau in Gironde, Nouvelle-Aquintaine, France.

One option to evaluate today's spring frost risk in Beychac-et-Cailleau is to adjust historically observed temperatures for today's conditions. This means that instead of looking at historically observed temperatures in the region, we detrend historical temperature observations against the underlying warming trend. This implies that the earlier years are regarded as if they had been warmer. This would have meant that the growing season would have started earlier, but also that nights would have been less cold. With this data at hand, one can evaluate the detrended minimum daily temperatures that would have appeared after this trend-adjusted day of vegetation emergence. *Figure 9* shows the lowest temperatures that appeared after the emergence of the vegetation from 1979 to 2021 in a cumulative distribution plot. In blue, it shows the cumulative distribution of the historically observed temperatures after the start of the risk exposure period in each year. In red are the detrended minimum temperatures that would have appeared after the detrended (earlier) start of the risk exposure period. The figure shows that in this particular commune, freezing temperatures would not have occurred more often, but that the frost events that occurred would have been more severe. This means that although temperatures have increased in Beychac-et-Cailleau, the shift of the risk period to an earlier time of the year has increased the risk of spring frost.

[6] *Note that this trend is small compared to what we estimate for example in Northern France and Germany. Also see the figure in the appendix.*

Going forward, higher frost risk requires premium rate increases to keep protecting fruit and wine growers

Looking back at temperatures of the past is no longer enough to appropriately assess weather risks in many cases. The climate is warming, the risk of spring frosts has changed, and will continue to change.

Accounting for the fact that the growing season today starts earlier than represented in the historical data is a must. Detrending of temperature data allows to better represent the spring frost risk at current conditions. Detrending temperature data for a warming trend has the effect that detrended daily minimum temperatures increase, but also that the modelled start of the growing season moves forward. From a frost risk perspective, the best case would be that any increase in minimum temperatures offsets the earlier start of the growing season. Yet, this is not what we observe. *Figure 10* shows return periods of spring frosts during the vegetation's exposure period when taking temperature trends into account all over Europe. It shows that we can expect more frequent frost events during the time that the vegetation is vulnerable, especially where frost risk was already relevant, and from Lower Saxony to Brandenburg. For instance, in a large area of Germany the risk of a frost event after the start of the growing season has increased by more than 200% compared to original historical data *(see Figure 11)*.

Risk exposure start (DOY of the year) from 1979 to 2021

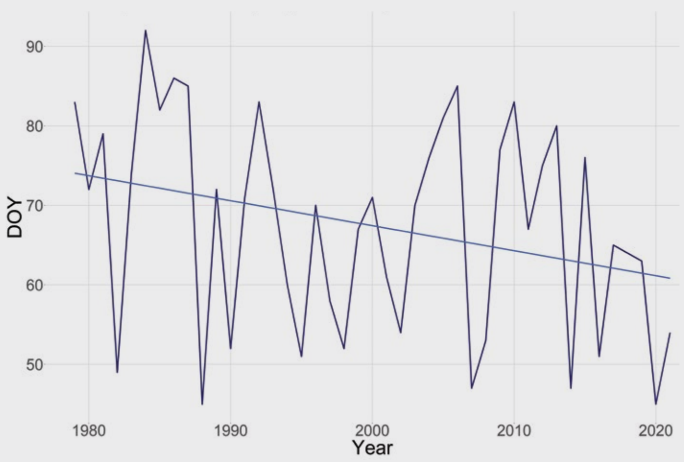


Figure 8: Estimated day of the year when risk exposure started in Beychac-et-Cailleau.

CDF plot of Tmin during growing season in Beychac-et-Cailleau

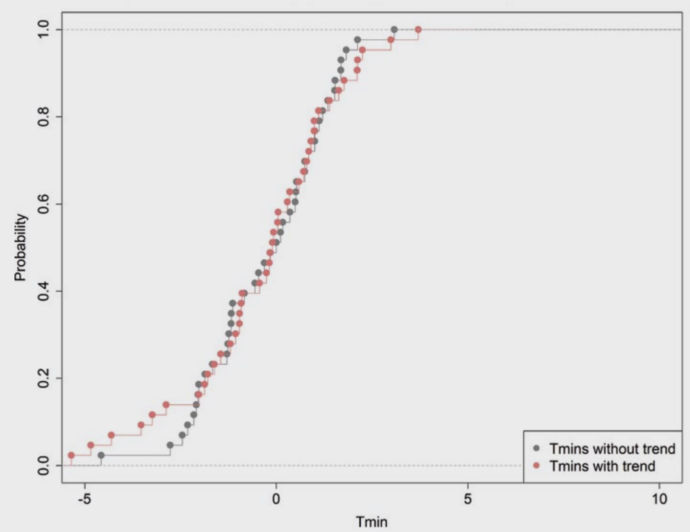


Figure 9: Cumulative distribution of historically observed and detrended minimum temperatures after the original and detrended start of the risk exposure period. The bottom left part of the figure shows that with the temperature trend taken into account, lower temperatures would have occurred during the growing season.

Change in spring frost frequency

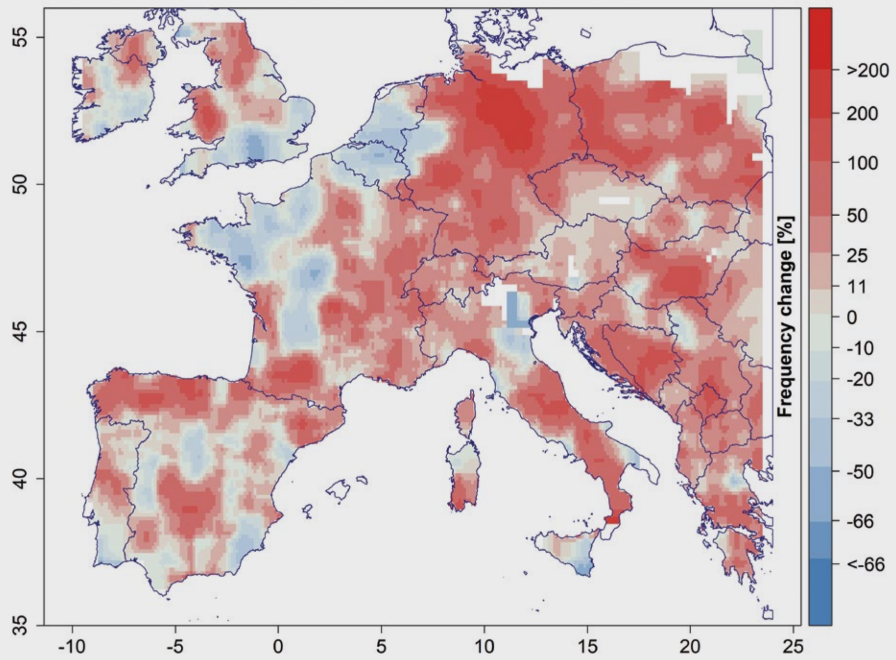


Figure 11: Relative change in frost frequency when taking temperature trends into account, i.e. relative change between Figure 10 and Figure 6.

Return period of a frost event during the growig season, detrended

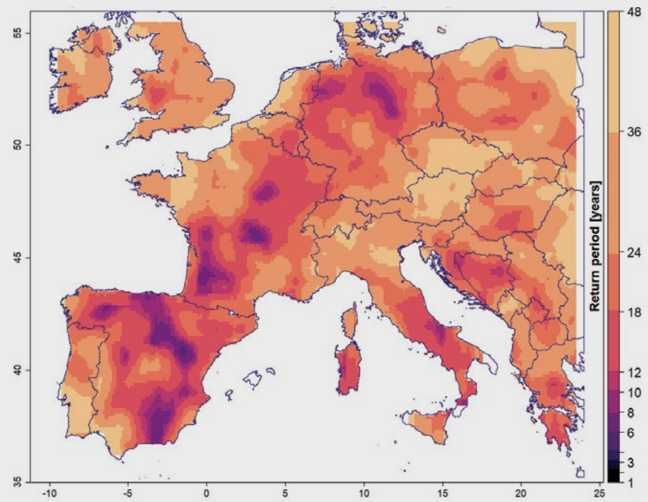


Figure 10: Estimated return period of a frost event during the growing season for today's conditions.

To a certain extent, it remains an empirical question how this change in frost frequency will affect agriculture losses at the farm level, because the impact of a frost event on agriculture production depends on the severity and the timing of the frost, on the crop and variety, the exact location (for example the hill side and slope) as well as on farmers' prevention measures. Nevertheless, we can calculate a first order estimate changes in losses from frost events by using a generic vulnerability function[7], considering that later and stronger frosts are more harmful to agricultural production. *Figure 12* shows that the pattern of change in agricultural losses is similar to the pattern of change in frost frequency. More specifically, under today's conditions, spring frosts would have been responsible for much higher losses (up to double) than what we have observed in the past in many regions. At the same time, it shows that there is a region around the Canal (Western France, South Western England, Coastal Belgian and the Netherlands), where we may expect fewer agricultural losses from spring frost.
Figure 13 shows this with the example of the commune Beychac-et-Cailleau in Gironde. With higher temperatures, in some years, temperatures no longer fell below 0° or the frost was less severe. However, more severe frost events would have occurred in or later in the growing season. In this particular example, average loss costs[8] would increase by 50%[9].

[7] *We specify a vulnerability function that estimates loss costs resulting from negative temperatures depending on frost severity and on the timing of frost (the number of days after the growing season started).*
[8] *Average loss costs are the share of the total insured value that gets lost in an average year.*

[9] *Note that the translation of frost occurrence to fruit and wine loss cost numbers are a result from an arbitrary estimated vulnerability function (an arbitrarily estimation of the impact that frosts have on fruit and wine production). Therefore, the loss costs should not be interpreted. However, the estimated change in loss costs between the original and the detrended model is robust over different specifications of the vulnerability function. In other words, to get an understanding of how average loss costs change with climate change, it is not very relevant how we quantify the impact of frosts on fruit and wine production.*

Change in spring frost loss costs

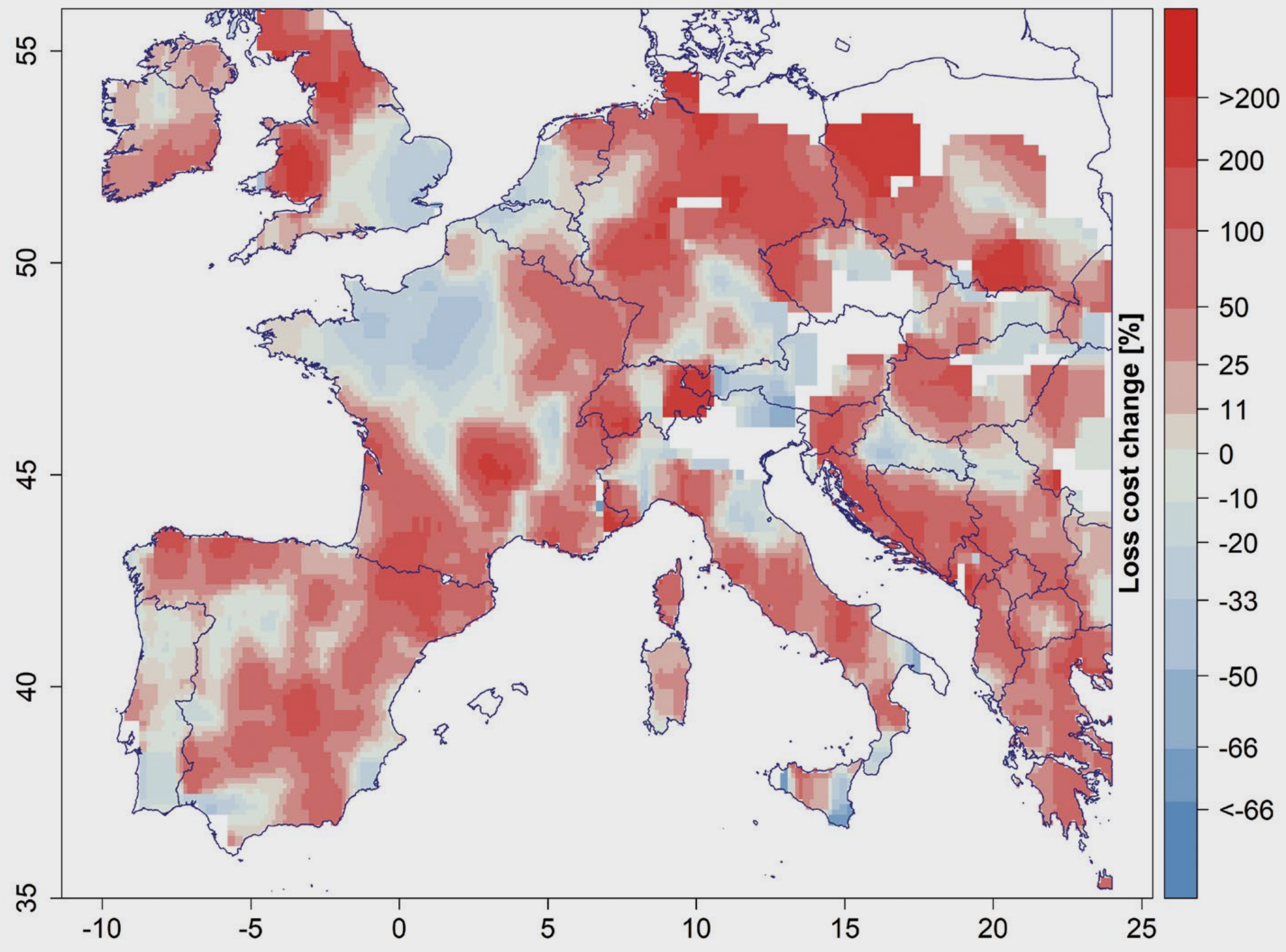


Figure 12: Change in loss costs estimates due to spring frosts when taking temperature increase into account.

CDF plot of spring frost loss costs in Beychac-et-Cailleau

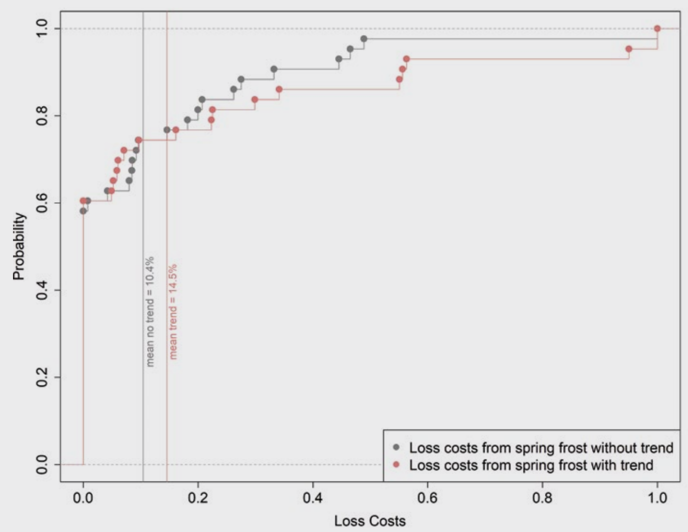


Figure 13: Effect on loss costs in the example of Beychac-et-Cailleau.

The advancing growing season has an important effect on frost risk, and so do minimum temperatures. While we do observe an increasing trend in minimum temperatures, climate change may also change the risk of more extreme events, for example through a changing frequency of cold air outbreaks[10]. While in this study we aim to evaluate historical observations in a context similar to today, there are additional system drivers to take into account.

While farmers have on-farm risk management tools to mitigate spring frost damages (for example outdoor heating systems, more frost-resistant varieties and irrigation systems), insurance solutions remain efficient risk transfer tools for fruit and wine growers. Currently, most crop insurance companies use historical loss experience to set the insurance rates. However, a pure experience-based rating approach may strongly under- (or over-) estimate the risk of spring frost for most regions in Europe due to earlier start of the vegetation period.

[10] *Also see Huang et al. (2021). Northern Hemisphere cold air outbreaks are more likely to be severe during weak polar vortex conditions. Nature Communications Earth & Environment. 2,147; Smith et a. (2020). Where do cold air outbreaks occur, and how have they changed over time? Geophysical Research Letters. 47,13.*

Methods and Data

Data

For this analysis, we used hourly ERA5 reanalysis temperature data (a global and consistent weather data set with hourly gridded data based on a combination of past weather observations with today's weather models) from 1979 to 2021. The data is produced by the European Centre for Medium-Range Weather Forecasts (ECMWF). From this data, we extracted daily minimum and maximum temperatures. The data has a grid size of 30km, and our analysis was done at this scale. We smoothed the images to increase visual appeal. The data has a latency of five days. The ERA5 data is freely accessible in the Copernicus Climate Change Service and is well documented. For more information see: https://confluence.ecmwf.int/display/CKB/ERA5%3A+data+documentation.

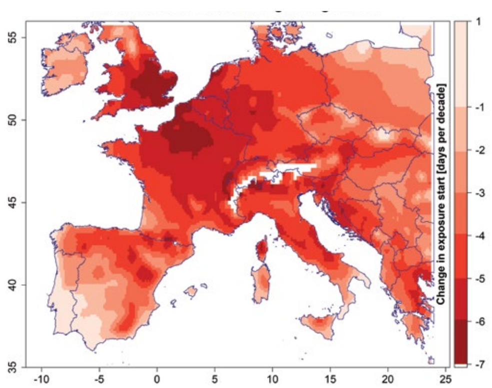
We selected a generic growing degree day model representing the entire vegetation rather than specific crop types. For obtaining more crop-specific results, the growing degree day models need to be calibrated to specific species and varieties reducing the error related to heat unit requirements for reaching different phenological phases. For example, the growing season for cherries and apricots starts earlier than for apple and pear trees or for vineyards. Also, different varieties can have different frost resistances.

To estimate frost frequency, we define frost events as events with minimum temperatures below -2°C.

To detrend minimum and maximum temperatures, we used a robust outlier resistant estimator to find a linear time trend for in each pixel. There were no large deviations in trends between neighboring pixels, which is why we went without estimating common regional trends. We find stronger increasing trends for maximum than for minimum temperatures.

We specify a vulnerability function that estimates loss costs depending on frost severity and the day of season (number of days since the growing season started). Note that the assumptions we take to specify the vulnerability function are arbitrary yet resulting changes in spring frost loss costs are robust over different specifications. We take the following assumptions: on day 1 of the season, a minimum temperature of -7°C leads to a loss cost of 100%, while loss costs occur from temperatures colder than -2°C (with a linear relationship for temperatures and loss costs in between, i.e. -4.5°C leads to 50% loss costs). We assume that the impact of a frost increases linearly with the day of the season, and therefore assume that on day 30, a minimum temperature of -5.5°C leads to a loss cost of 100%, while loss costs occur from temperatures colder than -0.5°C.

Advance in the start of the growing season from 1979 – 2021 in days per decade.



About the authors:

Willemijn Vroege is an Agriculture Underwriter with AXA XL's International Reinsurance business. Willemijn holds a Ph.D. in Agricultural Economics from ETH Zurich and has a strong interest in using (new) technologies to insure agricultural production, specifically in the context of climate change.

Willemijn is based in Zurich and can be reached at willemijn.vroege@axaxl.com

Niklaus Lehmann is a Senior Agriculture Underwriter with AXA XL's International Reinsurance business. Niklaus holds a Ph.D. in crop modelling from ETH Zurich and is always open to discussing new insurance solutions for protecting agricultural production.

Niklaus is based in Zurich and can be reached at niklaus.lehmann@axaxl.com

Beat Krauer leads the Agriculture Reinsurance Team at AXA XL. With a background in forestry engineering and statistics he is as passionate about the farming business as our clients and their customers. He sees genuine long-term partnership and an innovative mindset as crucial to helping clients take their business further.

Beat is based in Zurich and can be reached at beat.krauer@axaxl.com

axaxl.com