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Forecasting Tools and Risk Prediction Models for Decision Support in Fruit Production

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Contents

List of publications

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The abstracts of the following topic related contributions are reproduced in chapter 7:

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2) Whitney, C., Schmitz, C., Luedeling, Eike, 2024. Learn How to Make Accurate Estimates: Calibration Training with an Interactive Online Application, in: 2024 DSI Annual Conference Proceedings. Presented at the 55th Annual Conference, Phoenix, Arizona, pp. 849–864. https://decisionsciences.org/wp-content/uploads/FINAL_PROCEEDINGS_2024.pdf

3) Zimmermann, L., Kopton, J., Schmitz, C., Whitney, C., Balmer, M., Luedeling, E., 2025. The carbon footprint of training system selection in apple production. Acta Hortic. 449–456. https://doi.org/10.17660/ActaHortic.2025.1425.58

Summary

Tree fruit production in Germany is confronted with various risks that affect quality and reduce yields, such as disease infestation or weather events. The occurrence of late spring frosts often leads to cell damage, resulting in yield reduction and reduced fruit quality, e.g. due to 'frost rings' on the peel. With ongoing climate change, fruit trees tend to bloom earlier, which goes along with an increase in spring frost frequency during the last years in some regions.

In this thesis, I applied the decision analysis methodology to develop probabilistic models. Decision analysis allows for the inclusion of expert knowledge into the modelling procedure and accounts for uncertainty and variability of the model parameter values. Furthermore, I used Kriging Interpolation and process-based phenology modelling to produce countrywide maps of historic and future frost risk in apple production.

1. In chapter 2, I introduce ProbApple a model to make probabilistic forecasts of total apple yield and high-quality yield at four time points during the growing season (at full bloom, before fruit thinning, after June drop, and four weeks before harvest). Using a case study on 'Gala' apple in Rhineland, we showed the functionality and structure of the model and compared the high-quality yield in orchards with and without anti-hail netting.
2. In chapter 3, I analyze the frost frequency during and after apple bloom in the time periods 1993-2007 and 2007-2022 based on historic temperature and phenology data. We observed a trend toward earlier apple bloom and increasing frost frequency across nearly in the whole country. Frosts below 0°C occurred in all apple production regions, while only during a few frost events the temperatures fell below -2.2°C.
3. In chapter 4, I describe a decision support model to advise apricot producers on investments in frost protection. We compared yield effects and Net Present Value of candles, below-canopy irrigation, as well as mobile and stationary wind machines in relation to apricots production without frost protection. Despite an appreciable increase in yield, the additional income was not sufficient to cover the additional costs for frost protection.
4. In chapter 5, I present a comparison of eight frost protection measures (mobile or stationary wind machines, portable or tractor-mounted gas heaters, overhead or below-canopy irrigation, candles and pellet heaters) regarding their economic efficiency and yield effects in apple production using decision analysis. It turned out that overhead irrigation and stationary wind machines appear to be the most promising frost protection measures, but they do not necessarily increase farmers' revenues.
5. In chapter 6, I show maps for the future spring frost risk in German apple production from green tip stage until summer under four climate change scenarios for the years 2050 and 2085. The phenology forecast indicates that the current trend towards earlier apple blossom will continue in future. The effect of climate change of frost risks differs between regions and climate change scenarios. However, we showed that late spring frost will remain a challenge for apple production even at the end of the 21st century.

Overall, the forecasting tools, risk prediction models, and their results in this thesis may be useful for fruit growers to make informed decisions in short- and long-term planning. They can be used by policymakers as a reliable source of information and serve scientists as a base for further development of probabilistic models in fruit production.

Zusammenfassung

Die Baumobsterzeugung in Deutschland, ist mit vielseitigen Risiken konfrontiert, welche die Qualität beeinträchtigen und die Erträge mindern, z. B. Krankheitsbefall oder Wetterereignisse. Das Auftreten von Spätfrösten im Frühjahr führt häufig zu Zellschäden und damit zu Ertragsminderungen und reduzierter Fruchtqualität, z. B. durch „Frostringe“ auf der Schale. Mit dem fortschreitenden Klimawandel blühen Obstbäume tendenziell früher, was in einigen Regionen mit einer Zunahme der Spätfrosthäufigkeit in den letzten Jahren einherging.

In dieser Arbeit habe ich die Methodik der Entscheidungsanalyse angewandt, um probabilistische Modelle zu entwickeln. Die Entscheidungsanalyse ermöglicht es, Expertenwissen in das Modell einzubeziehen und die Unsicherheit und Variabilität der Modellparameterwerte zu berücksichtigen. Darüber hinaus habe ich Kriging-Interpolation und prozessbasierte phänologische Modellierung verwendet, um landesweite Karten des Frostrisikos im Apfelanbau zu erstellen.

1. In Kapitel 2 stelle ich ProbApple vor, ein Modell zur probabilistischen Vorhersage des Gesamtertrags und des Qualitätsertrags von Äpfeln zu vier Zeitpunkten während der Vegetationsperiode (zur Vollblüte, vor dem Ausdünnen der Früchte, nach dem Junifall und vier Wochen vor der Ernte). Anhand einer Fallstudie über den Apfel ‚Gala‘ im Rheinland zeigen wir die Funktionsweise und Struktur des Modells und vergleichen den Qualitätsertrag in Obstanlagen mit und ohne Hagelschutznetz.
2. In Kapitel 3 analysiere ich die Frosthäufigkeit während und nach der Apfelblüte in den Zeiträumen 1993-2007 und 2008-2022 anhand von historischen Temperatur- und Phänologiedaten. Wir konnten wir einen Trend zu einer früheren Apfelblüte und einer zunehmenden Frosthäufigkeit in fast ganz Deutschland feststellen. Fröste unter 0°C traten in allen Apfelanbauregionen auf, während die Temperaturen nur bei wenigen Frostereignissen unter 2,2 °C fielen.
3. In Kapitel 4 beschreibe ich ein Entscheidungsmodell zur Beratung von Aprikosenproduzenten hinsichtlich einer Investitionen in Frostschutz. Wir haben den Ertragseffekt und den Kapitalwert von Kerzen, Unterkronenbewässerung sowie mobilen und stationären Windmaschinen im Verhältnis zur Aprikosenproduktion ohne Frostschutz verglichen. Trotz einer deutlichen Ertragssteigerung reichten die zusätzlichen Erträge nicht aus, um die Mehrkosten für den Frostschutz zu decken.
4. In Kapitel 5 stelle ich einen Vergleich von acht Frostschutzmaßnahmen (mobile oder stationäre Windmaschinen, mobile oder traktormontierte Gasheizgeräten, Überkronen- oder Unterkronenbewässerung, Kerzen und Pelletheizungen) hinsichtlich ihrer Wirtschaftlichkeit und Ertragseffekte im Apfelanbau mittels Entscheidungsanalyse vor. Es zeigte sich, dass Überkronenberegnung und stationäre Windmaschinen die vielversprechendsten Frostschutzmaßnahmen zu sein scheinen, aber nicht unbedingt die Einnahmen der Landwirte erhöhen.
5. In Kapitel 6 zeige ich Karten für das zukünftige Spätfrostrisiko in der deutschen Apfelproduktion vom Blattknospenaufbruch bis zum Sommer unter vier Klimawandelszenarien für die Jahre 2050 und 2085. Die Phänologieprognose zeigt, dass sich der derzeitige Trend zur früheren Apfelblüte auch in Zukunft fortsetzen wird. Die Auswirkungen des Klimawandels auf die Frostgefahr sind je nach Region und Klimawandelszenario unterschiedlich. Wir haben jedoch gezeigt, dass Spätfröste auch am Ende des 21. Jahrhunderts noch eine Herausforderung für die Apfelproduktion darstellen werden.

Insgesamt können die Prognoseinstrumente, Risikovorhersagemodelle und ihre Ergebnisse in dieser Arbeit für Obstbauern nützlich sein, um fundierte Entscheidungen für die kurz- und langfristige Planung zu treffen. Sie können von politischen Entscheidungsträgern als zuverlässige Informationsquelle genutzt werden und Wissenschaftlern als Grundlage für die weitere Entwicklung probabilistischer Modelle im Obstbau dienen.

Abbreviations and Units

%	percent
&	and
€	Euro
°C	degrees Celsius
°E	degrees east, measure for longitude
°N	degrees north, measure for latitude
Approx.	approximately
BBCH	Biologische Bundesanstalt (German Federal Biological Research Centre for Agriculture and Forestry), Bundessortenamt (German Federal Office of Plant Varieties) and Chemical Industry)
BMEL	Bundesministerium für Ernährung und Landwirtschaft
BW	Baden-Württemberg
CDC	Climate Data Center
cm	centimeter
cm^3	cubic centimeter
CMIP5	phase 5 of the Coupled Model Intercomparison Project
CMIP6	phase 6 of the Coupled Model Intercomparison Project
CO_2	Carbon dioxide
DWD	Deutscher Wetterdienst
e.g.	*exempli gratia*
et al.	*et alia*
EVPI	Expected Value of Perfect Information
Fig.	figure
GCM	Global Circulation Models
GDH	Growing Degree Hours
GenSA	generalized simulated annealing
h	hour
ha	hectare, 1 ha = 10.000 m^2
i.e.	*id est*
INA	icenucleation active
IPCC	Intergovernmental Panel on Climate Change

kg	kilogram
km	kilometer
KOB	Kompetenzzentrum Obstbau Bodensee
m	meter
m a.s.l	meters above sea level
m^2	square meter
NINA	non-icenucleation active
NPV	Net Present Value
PLS	Partial Least Squares
pp	Percentage points
Q1, Q2, Q3	Question 1, question 2, question 3
Q5	5 % Quantile
Q95	95 % Quantile
R^2	coefficient of determination
RCP	Representative Concentration Pathway
RLP	Rhineland Palatinate
RMSE	Root Mean Square Error
RPIQ	Ratio of performance to inter-quartile distance
SSP	Shared Socioeconomic Pathway
t	ton
Tab.	table
tp1	first ProbApple prediction time point: at full bloom
tp2	second ProbApple prediction time point: before fruit thinning
tp3	third ProbApple prediction time point: after June drop
tp4	forth ProbApple prediction time point: four weeks before the estimated harvest date
US	United states of America
VIP	Variable Importance in Projection
W	Watt
ρ	volumetric mass density
etc.	*et cetera*
vs.	*versus*

Chapter 1: Introduction

Fruit orchards are an important part of the agricultural landscape. They are primarily used to produce healthy food. In addition, they hold aesthetic and cultural value, as people appreciate orchards as a landscape feature, especially during the flowering period (Baumgärtner and Bieri, 2006). With their long stand duration and structurally diverse vegetation, fruit orchards provide habitats for a broad range of species, including wild bees, hoverflies, bugs, spiders, ground beetles and other insects, as well as birds and bats (Jaenicke and Hamm, 2022). CO_2 sequestration (Zanotelli et al., 2015) represents another aspect of the numerous ecosystem services offered by fruit orchards (Demestihas et al., 2017).

Fruit production in Germany is dominated by tree fruit cultivation, which accounts for 87% of the total fruit yield. The most important tree fruit species is apple (*Malus domestica*), covering about 45% of the total fruit production area and contributing 78% of the yield (Garming, 2023). Other commercially grown tree fruits include pears, sweet and sour cherries, plums and mirabelles. A small number of producers also grow apricots, peaches and walnuts. In addition to tree fruits, strawberries and berries, for example black or red currants and blueberries, are produced.

Over the last twenty years, the number of fruit producing farms in Germany has decreased by approximately half, from 13,671 in 2002 to 6,510 in 2022 (Destatis, 2024). The remaining growers are facing major economic and social challenges. Those challenges include i) the production of high quality apple, while a broad range of agronomic, environmental and genetic factors influence fruit quality (chapter 1.2), ii) severe yield reducing events, such as late spring frosts (chapter 1.3) and iii) the ongoing climate change and its impacts (chapter 1.4). Furthermore, fruit growers in Germany lack access to suitable plant protection agents. The limited number of approved agents leads to indication gaps and often prevents rotation between different substances, which is necessary to avoid resistances (Dirksmeyer et al., 2024). At the same time, fruit growers struggle to find sufficient labor and to produce fruits profitably under the current cost and income conditions (Dirksmeyer et al., 2024; Muder et al., 2024).

In order to preserve the benefits of fruit growing in the future, easy-to-use and reliable tools are needed to support growers in their short- and long-term planning in these challenging times.

1.1 Background - apple production in Germany

The main apple-growing regions in Germany are the “Altes Land” in the north, the “Lake Constance region” in the south, Saxony in the east and the “Rhineland” in the west of the country. In total, apples are cultivated on an area of around 32,990 ha. In 2024, 8,719 thousand tons of apple were produced, of which 73.2 % were marketed as dessert apples (Destatis, 2025).

The major part of the apple production area is managed according to the guidelines of “Integrated production”, developed by the Bundesausschuss Obst und Gemüse (2006). On about 24% (7950 ha) of the apple production organic apples are produced (Destatis, 2025). The most common varieties are ‘Elstar’, ‘Gala’ and ‘Braeburn’ (Destatis, 2025). Domestic production is sufficient for a self-sufficiency rate of 40.9 % (financial year 2017/2018, frost damage year (Faust and Herbold, 2017)) to 67.7 % (financial year 2022/2023) during the last years (Dirksmeyer et al., 2024).

In Germany, apple trees usually bloom in late April to early May for a period of about 14 days from the start to the end of bloom. There are slight differences between varieties, for example, in the Rhineland during the period 1988-2017, the flowering of ‘Cox orange’ and ‘Golden Delicious’ began on average on April 26, while ‘Roter Boskoop’ started blooming five days earlier, on April 21 (Kunz and Blanke, 2022). Depending on the variety, most commercially grown are ready for harvest between the end of August (e.g. ‘Delbarestivale®’) and the beginning of November (e.g. ‘Cripps Pink‘) (Büchele, 2018).

1.2 Challenge 1 - Apple fruit quality

There is no general definition of quality that applies across all areas of life (Hsu et al., 2019). In fruit production, the term refers to the properties that fruit must possess in order to meet the requirements of the supply chain (Costa, 2019). A high fruit quality is crucial for the marketability, pricing (Badiu et al., 2015), as well as storability (Büchele, 2018) of harvested apples.

Apple quality parameters can be divided into external and internal attributes. External quality parameters describe the visual characteristics of the apple including fruit size and shape, absence of defects and peel color (Musacchi and Serra, 2018). Many of these parameters are used in the European Union to categorize apples into commercial classes (European Commission, 2004). Internal quality parameters describe the attributes that are not visible from the outside. They include the texture and firmness of the fruit flesh, as well as its composition, e.g. the starch and soluble solid content, dry matter and acidity (Musacchi and Serra, 2018).

1.2.1 Consumer and retailer preferences

The visual appearance of apples, e.g. color or damages, influences how much consumers like apples (Bolos et al., 2021; Normann et al., 2019). Further quality parameters such as safety and taste also play an important role in the purchasing decision (Gustavsen and Milford, 2024). Consumer preferences differ between countries (Bonany et al., 2014) and consumer age (Racskó et al., 2009).

Quality standards are based on the assumption that consumers prefer fruits that always look the same (Normann et al., 2019). In recent years, several studies have shown that consumers would also purchase apples with slight imperfections if a price discount is given (de Hooge et al., 2017; Hueppe and Zander, 2024). Some consumers would even pay the same price as for flawless apples, especially if it is clearly communicated that the internal quality is not affected by the imperfections (Hueppe and Zander, 2024). However, representatives of producer organizations report that consumers tend to choose perfect-looking, uniform apples and do not want to buy apples with imperfections (de Hooge et al., 2018). A bad experience with the quality of apples influences consumers' habits in the future and can lead to them not buying apples for a while or switching to other varieties or fruits (Harker et al., 2003).

Defining and applying visual quality specifications is an important step in delivering high quality fruit in the food supply chain (de Hooge et al., 2018). The various players along the apple food supply chain have different priorities. Djekic et al. (2019) analyzed those priorities and showed that fruit growers consider cultivar and yield including share of first-class apples as the most important quality factors. For cold storage, the handling of fruit, share of first-class and fruit defects are crucial factors, while retailers focus on the type of cold storage, physical defects, apple cultivar, fruit color, packaging and the ratio between quality and price. Consumers pay attention to the price, assortment and product placement of the apples (Djekic et al., 2019).

1.2.2 Influences on apple quality

Apple quality at harvest is influenced by various agronomic, environmental and genetic factors (Musacchi and Serra, 2018). In the further course of the food supply chain, apple quality is influenced by the harvesting conditions and technique (Hussein et al., 2020) and the type of storage (Radenkovs and Juhnevica-Radenkova, 2018). The focus of this work is on the quality influences and possible damage causes before harvest. The quality-reducing factors in the following sections serve as an overview of possible damage categories and provide examples without claiming to be exhaustive.

Biotic damage

Apple trees can be affected by various diseases and pests, including fungal, bacterial and virotic pathogens as well as insects or animals. The fungal disease which requires the highest control effort of all fungal pathogens is apple scab (Büchele, 2018). Apple scab is caused by *Venturia inaequalis* and forms scab lesions on leaves (Figure 1 H) and fruits which make the apple fruits unmarketable (Bowen et al., 2011). A second example of fungal diseases is powdery mildew which is caused by *Podosphaera leucotricha* (Figure 1 I). Fruits developing from infected buds are often small, stunted and show russeting damage (Strickland et al., 2021). Fruit mummies (Figure 1 F) could serve as an overwintering place for the causal agents of black rot and sooty blotch (Beer et al., 2015).

Fire blight caused by *Erwinia amylovora* is an example of a bacterial disease which plays a relevant role in German apple production. It can damage several plant organs (van der Zwet and Beer, 1999) and spreads rapidly within the infected tree, causing damage in form of yield losses or the loss of whole trees (Vanneste, 2000). Virus diseases such as the apple mosaic virus and rubbery wood disease agent, may cause yield losses of up to 46% (Cembali et al., 2003). The symptoms of the apple mosaic virus vary and depend on the cultivar and range from asymptomatic infection to severe yield decrease (Grimová et al., 2016).

Several insect species e.g. aphids or mites have the ability to reduce yield and quality in apple orchards during the course of the year (Büchele, 2018). A common pest is the codling moth *Cydia pomonella* which may infest 30% to 50% of the fruits if no control takes place. The larva invades the apple fruits and feed within fruits. In older stage, the larva leaves the apple and leaves an exit hole (Figure 1 B) (Pajač et al., 2011). In recent years the mediterranean fruit fly *Ceratitis capitata* (Wiedemann) (Lopes et al., 2023; Wernicke et al., 2024) and the brown marmorated stinkbug (*Halyomorpha halys* Stål) (Hess et al., 2022) have been frequently discussed among fruit growers and advisors.

Further animals, which damage apple by feeding them are for example the European hare (*Lepus europaeus*) or several bird species. European hares only reach apples hanging low on the tree and may feed on them (Figure 1 A). Several studies on birds have shown that the damage caused by bird pecking ranges between 0% and 7.4%, but mostly around 2% of the apples (Anderson et al., 2013; Elser et al., 2019; Lindell et al., 2016; Mangan et al., 2017; Peisley et al., 2016).

Abiotic damages

Hail events are observed during the whole growing period, but most frequently in the summer months June and July (Puskeiler, 2013). Hailstorms harm blossoms, fruits or leaves (Figure 1 G) and the damaged parts of the trees are susceptible to further disease and insect damage (Rana et al., 2022). Fruit growers can invest in anti-hail nets to reduce the amount of hail damage or insurances to mitigate the economic consequences of hail damage (Gandorfer et al., 2016).

Besides hail, apple trees and fruits can be mechanically injured by storm or through management practices. Extreme storms could uproot trees and destroy the anti-hail nets as happened in northern Italy in 2020 (De Petris et al., 2021). Minor mechanical damage occurs during intensive work in the orchard, e.g. during summer pruning (Bound and Summers, 2001).

Sunburn is caused by excess solar radiation and/or high temperatures at the fruit surface (Racsko and Schrader, 2012). Fruit growers try to reduce sunburn damage with anti-hail nets (Dayioglu and Hepaksoy, 2016), by evaporative cooling (Racsko and Schrader, 2012) and spraying kaolin (Blanke, 2011; Wiebusch, 2019).

Drought stress caused by limited water availability, can influence fruit yield and quality. The effects for the orchards vary depending on the severity and duration of the drought as well as the point during the season in which the drought occurs and the rootstock of the tree (Aras and Keles, 2019; Pérez-Pastor et al., 2016). While a water deficit in the first two months after bloom reduces fruit size and increase natural fruit drop (i.e. decreasing the number of apples per tree) (Behboudian et al., 1998; Pérez-Pastor et al., 2016), mild drought stress late in the season may enhance fruit quality (Wang et al., 2019).

Frost is another important abiotic damage factor. See chapter 1.3 for more information.

Physiological disorders

Physiological disorders have the potential to greatly reduce apple fruit quality and marketability. Their symptoms can appear before harvest, but often only become visible after storage (Büchele, 2018).

Bitter pit is a frequent physiological disorder in apple. It may occur pre- and post- harvest and is characterized by small, brown, spherical spots of dead cells on the apple skin (Figure 1 C), which are bitter in taste (Jemrić et al., 2017). The mechanisms behind the development of bitter pit are not completely clear (Jemrić et al., 2017; Torres et al., 2024). It is known that calcium plays a role and that several agronomic factors including cultivar, rootstock and training system, but also environmental factors such as climate and soil influence bitter pit occurrence (Torres et al., 2024).

Apple fruits affected by water core have a liquid filling (instead of air) in some of the intercellular areas in the flesh. Mild symptoms are reversible shortly after harvest, but the disorder can also develop further to flesh browning during storage (Büchele, 2018). The occurrence of water core depends of the level of sorbitol oxidase, the transport capacity of the apple fruit tissue for water and/or sorbitol as well as pre-harvest fruit temperatures (Suzuki et al., 2003; Yamada et al., 1994).

Further physiological disorders are lenticel blotch pit, scald, skin spots, soft scald, core flush and core browning. These disorders usually appear during storage, but the conditions before harvesting influence the frequency of occurrence (Büchele, 2018).

Visual appearance

Peel color of apples strongly depends on the genetics of an apple variety, but epigenetics also play a role (Wang et al., 2020). In German fruit growing regions, light is a limiting factor for the fruit color of apples (Blanke, 2015). Cool nights and a considerable difference between night and day temperature support the formation of fruit color (Lakatos et al., 2008). Further influencing factors are the nutrient supply and the management practices conducted in the orchard (Blanke, 2015). Fruit growers can improve fruit color by the use of evaporative cooling (Blanke, 2015), reflective ground covers (Meinhold et al., 2011), pneumatic defoliation and summer pruning (Andergassen et al., 2023).

Russeting (Figure 1 D & E) is a peel defect which can be caused by various sources, including cell injury due to freezing, pH of rain water, relative humidity and rainfall in the first weeks after bloom, fungal, bacterial and virotic pathogens, mites, nutritional imbalance and the application of agrochemicals such as copper- and sulfur-based products (Sharma et al., 2025). The susceptibility for russeting varies between apple cultivars (Khanal et al., 2013).

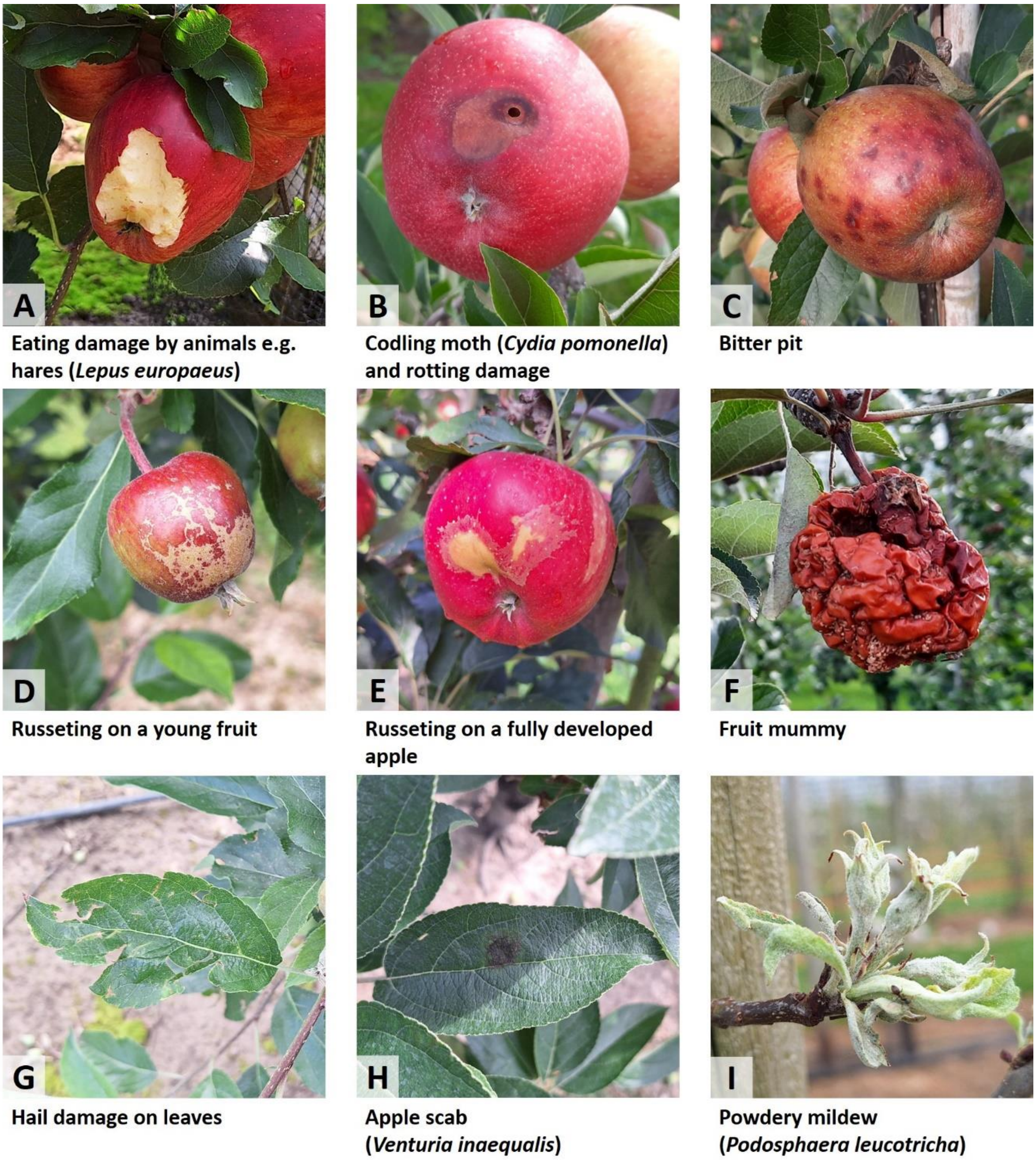

Figure 1: Examples for quality reducing factors and diseases in apple production. Pictures taken in the experimental orchard in Klein-Altendorf (Rheinbach, Germany) in 2024.

1.3 Challenge 2 - Late spring frosts

One important risk for low yields and poor fruit quality is the occurrence of late spring frosts. Late spring frost are freezing events that occur in spring, after plants already begun their development. A general definition describes them as freezing events that occur after the trees have already been exposed to a substantial amount of warming (Zohner et al., 2020). Focusing on certain species and time points, late spring frosts can be more narrowly defined as frost occurrence after budbreak (Mosedale et al., 2015) or after the first flowers have opened (Hoffmann and Rath, 2013). Commonly a frost is defined as an air temperature of 0°C or lower, measured between 1.25 m and 2 m above ground (Snyder and Melo-Abreu, 2005). Other thresholds, such as -2°C (Hoffmann and Rath, 2013) or

-2.2 °C (Unterberger et al., 2018) are sometimes used to account for the fact that buds can survive light frosts without damage.

Alternative terms for late spring frosts are false spring (Bosdijk et al., 2024) and blossom frost (Hoffmann and Rath, 2013).

1.3.1 Types of frost

Frost events can be divided into radiation frosts and advection frosts (also known as wind frosts) (Lalic et al., 2018; Perry, 1998; Snyder and Melo-Abreu, 2005). Some authors consider evaporation frost as another frost type (Baab et al., 2016).

Radiation frosts usually occur in nights with a clear sky and calm winds (Perry, 1998). During the night, the soil releases heat in form of long-wave radiation, which usually can be reflected by clouds. However, when the sky is cloudless, this heat is released into the atmosphere, resulting in a net loss of energy and a temperature drop near the ground (Baab et al., 2016; Snyder and Melo-Abreu, 2005). Despite the flux of sensible heat from the air above and the soil below to the surface, the near-surface temperature drops rapidly, leading to a temperature inversion. The thickness of the inversion layer depends on topographical and weather conditions (Snyder and Melo-Abreu, 2005) and typically ranges between 9 and 61 meters (Perry, 1998). Radiation frost can be further categorized into 'hoar frost' (Figure 2) and 'black frost'. Hoar frost occurs when atmospheric moisture condenses and freezes on surfaces, forming visible ice crystals. Events where the temperature drops below 0°C, but no ice crystals form on the surface are called 'black frosts'. This occurs when air humidity is low and surface temperatures remain above the ice point (Lalic et al., 2018; Perry, 1998; Snyder and Melo-Abreu, 2005).

Figure 2: Hoar frost on apple flowers and leaves on 23rd of April 2024 in Klein-Altendorf (Rheinbach, Germany)

Advective frosts occur when the movement of air masses brings sub-freezing air into a region (Snyder and Melo-Abreu, 2005). These events are usually accompanied by wind speeds exceeding 2.2 m/s. Unlike radiation frosts, there is no inversion layer and no ice crystals form on the plant surface (Perry, 1998). Cloud cover may be present and temperatures often remain below freezing even during the day (Snyder and Melo-Abreu, 2005).

Evaporation frost can occur when the plant organs are wet, e.g. due to rain, and a dry wind passes through the orchard (Baab et al., 2016; Pauthier et al., 2022). As water evaporates from the plant surface, it requires energy in the form of heat. This vaporization enthalpy is drawn from the plant tissue and the surrounding air, causing the plant surface to cool. As a result, frost damage may even occur when the air temperature is above 0°C (Baab et al., 2016).

1.3.2 Late spring frost damage

Late frosts in spring can damage the buds (Figure 3), blossoms and young fruit of fruit trees. The extent of the damage depends on the temperature and the phenological stage of the plant (Ballard et al., 1981). Susceptibility to frost damage varies between tree species (Proebsting and Mills, 1978) and even among cultivars (Aygün and Şan, 2005). Furthermore, factors such as plant acclimation, frost duration and the rate of temperature decrease influence the severity of frost damage (De Melo-Abreu et al., 2024).

In most of the times, cellular damage by frost is caused by extra-cellular freezing, i.e., the formation of ice crystals in the extra-cellular space of the plant (Rodrigo, 2000). The damage can result from dehydration of the plant cells as well as from the mechanical damage of membranes and tissues by the ice crystals (Burke et al., 1976). However, plants have several mechanisms of frost hardiness that allow them to survive a few degrees below 0°C (Hillmann et al., 2020). One common mechanism is supercooling, in which the liquid contents of plant tissue cool below 0°C without crystallization (Modlibowska, 1962). In other situations, frost damage can occur even when the air temperature (usually measured as dry-bulb temperature) is at or slightly above 0°C. This is due to evaporation cooling, where the wet-bulb temperature, which describes the temperature on a wet surface, can be considerably lower. As a result, frost damage may occur on wet parts of the plant, e.g. following rainfall during the day (Snyder and Melo-Abreu, 2005).

Figure 3: Damaged apple flower bud ('Gala Alvina') on 18th of April 2023, after a frost event on 4th of April 2023 in Klein-Altendorf (Rheinbach, Germany)

After a frost event, the affected buds are either shed, or recover and develop to fruits. Fruits from recovered buds often show signs of frost damage e.g. in form of unusual shapes, appearance and size (Rodrigo, 2000). A well-known symptom of frost damage is the formation of "frost rings", a russeted band around the apple fruit (Thalheimer, 2019). Beside yield loss and reduced external quality frost causes also changes in the internal status of buds and fruits. Shortly after the frost, the contents of glucose, fructose, sucrose, sorbitol and total sugars are increased in damaged apple and pear flowers (Hudina and Štampar, 2006). The influence of frost on the composition of the fruit has been shown also at harvest time. Apples with frost rings have a higher content of fructose in their flesh and directly under the rings a higher content of sorbitol and malic acid as apples without frost damage (Cebulj et al., 2021).

Yield loss and quality reduction due to frost events present an economical challenge for fruit growers. For example, a severe frost in spring 2017 affected fruit growers across 20 European countries resulting in yield losses up to 80% and an estimated total economic loss of 3.3 billion Euros (Faust and Herbold, 2017). Even milder frosts can decrease farm-level revenues. Dalhaus et al. (2020) modeled that the revenue of a fruit grower decreases by 2.05% when an apple orchard is exposed to -4 °C for just one hour.

1.3.3 Frost protection

Farmers can invest in a broad range of protection measures to mitigate the damage from late spring frosts (Table 1). The available frost protection measures are usually categorized into passive and active measures. Passive measures are implemented in advance of potential frost events, often as part of long-term orchard planning. In contrast, active measures are applied shortly before or during the frost event itself (De Melo-Abreu, 2018). Most active protection measures used in fruit orchards are suitable to counter radiation frost, but offer only limited protection against advection frosts (Snyder and Melo-Abreu, 2005).

Table 1: Overview about important frost protection measures for fruit orchards. Abrreviations: NINA = non-icenucleation active, INA = icenucleation active

	Measure	Mechanism	Comment	Source/Further information
Active	Sprinkler irrigation - Overhead - Blow-canopy	release of sensible heat during the freezing of water	High water consumption	(Snyder and Melo-Abreu, 2005)
	Candles	Releasing energy to the orchard by burning paraffin	High labor requirement	(Lakatos and Brotodjojo, 2022; Snyder and Melo-Abreu, 2005)
	Heaters	Releasing energy to the orchard liquid, solid or gas fuel	Various types of heaters are available	(Snyder and Melo-Abreu, 2005)
	Gas heaters • portable • trailed	Phase transition	Requires calm weather, Protection efficacy is controversially discussed among experts	(Coman et al., 2020; Nariyanpalli et al., 2021)
	Wind machine • Stationary • Mobile	Using the temperature inversion and mix warmer air from above with colder air near surface	Requires inversion, protection efficacy depends on the inversion strength and technology	(Beyá-Marshall et al., 2019; Ribeiro et al., 2006)
	Helicopter	Flying over the protected area to move warm air from above to the surface	Requires inversion, high costs	(Snyder and Melo-Abreu, 2005)
	Selective Inverted Sink (SIS)	Using the temperature inversion and mix warmer air from above with colder air near surface by a horizontally installed axial fan	Requires inversion	(Hu et al., 2018; Yazdanpanah and Stigter, 2011)
Passive	Site selection	Select sites with comparatively low frost frequency i.e. avoid cold spots	Consider cold air drainage, slope and aspect, and soil type in site selection	(Snyder and Melo-Abreu, 2005)
	Mowing grass and herbs	enhancing radiation absorption by the soil → improved energy transfer and storage in the soil	Should be done in advance to the frost period	(Snyder and Melo-Abreu, 2005)
	Plastic covers	slow heat loss from the surface at night	Slight protection, about 1°C	(Lang, 2014; Snyder and Melo-Abreu, 2005)
	Application of NINA-bacteria	Competition between INA and NINA bacteria	No common practice in Germany	(Lindow, 1983)

1.4 Challenge 3 – Climate change

1.4.1 Climate change

According to the Intergovernmental Panel on Climate Change (IPCC), climate change is defined as: ”A change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. Climate change may be due to natural internal processes or external forcings such as modulations of the solar cycles, volcanic eruptions and persistent anthropogenic changes in the composition of the atmosphere or in land use.” (IPCC, 2023).

Between the time periods 1850-1900 and 2011-2020, the global surface temperature increased by 1.1°C, mainly caused by human activities that have led to the emission of greenhouse gases (IPCC, 2023). This temperature rise has been accompanied by an increase in weather and climate extremes, which in turn cause negative impacts, losses and damages to nature and people all over the world (IPCC, 2023).

The Shared Socioeconomic Pathways (SSPs) are five scenarios describing possible future development of the world’s society and can be used for climate research. The SSPs outline alternative trajectories of global socio-economic development and related levels of challenges for mitigation and adaptation to climate change, independent of climate change itself or specific climate policies (O’Neill et al., 2016). O’Neill et al. (2017) presented the key characteristics of each pathway:

- SSP1 represents a scenario where the world transitions towards a more sustainable future. The development of environmentally friendly technologies leads to improved resource use efficiency. In this scenario, the challenges for both mitigation and adaptation are relatively low.
- SSP2 assumes that social, economic and technological development will continue along the trajectory of past trends. There is slow progress towards sustainable development goals, but inequalities persist globally. In this scenario, the challenges for both mitigation and adaptation are moderate.
- SSP3 is characterized by increasing rivalry between countries and regions. Growing competitiveness and the rise in conflicts lead to a policy shift towards national and regional interests, with some countries adopting more authoritarian forms of government. In this scenario, the challenges for both mitigation and adaptation are high.
- SSP4 assumes a world with strong inequality between societies (across and within countries) – those that are knowledge and capital-rich versus those that are poorly educated and dependent on high-labor economies. As a result, social cohesion declines. In this scenario, the challenges for mitigation are low, but the challenges for adaptation are high.
- SSP5 represents a future driven by fast economic growth, accompanied by high demand for resources and energy. This development is strongly reliant on fossil fuels, with limited awareness of environmental problems in policymaking. In this scenario, the challenges for mitigation are high, but the challenges for adaptation are low.

The SSPs are combined with a forcing pathway showing the expected change in radiative forcing. The Representative Concentration Pathways (RCPs) as part of Phase 5 and 6 of the Coupled Model Intercomparison Project (CMIP5 and CMIP6) can be used for this purpose (O’Neill et al., 2016). The RCPs cover a board range of potential future radiative forcing levels. The lowest forcing level, 2.6 W/m^2, represents a mitigation scenario, while the highest forcing level, 8.5 W/m^2, assumes very high greenhouse gas emissions (van Vuuren et al., 2011). A forcing level of 7.0 W/m^2 describes an unmitigated baseline scenario (O’Neill et al., 2016).Climate change is expected to challenge agricultural production and reduce global yields (Calzadilla et al., 2013; Wiebe et al., 2015). Although increased

CO_2-concentrations have a positive effect on plant productivity, this benefit is insufficient to offset the negative impacts of increasing temperature and changing precipitation patterns (Calzadilla et al., 2013). Extreme weather events, including temperature extremes, heat waves and droughts, cause major problems in horticulture (Bisbis et al., 2019). In addition, pest pressure is expected to increase due to faster reproduction, expanded geographical ranges, higher overwintering rates and raised risk of outbreaks of insect transmitted diseases (Skendžić et al., 2021).

1.4.2 Changes in tree phenology and late spring frost frequency

Ongoing climate change influences the flowering times of temperate fruit trees. Kunz and Blanke (2022) reported an advance of 11–14 days in the flowering of apple (‘Boskoop’, ‘Golden Delicious’ and ‘Cox orange’) and pear (‘Alexander Lucas’) in the Rhineland (Germany) between 1958 and 2015. Similar trends were observed for ‘Idared’ and ‘Golden Delicious’ apples in Dresden-Pillnitz, Germany (Lempe et al., 2022). In neighboring countries, such as France and Switzerland, a shift towards earlier apple blossom has also been documented (Atauri et al., 2010; Vitasse et al., 2018).

This shift in flowering time has been accompanied by an increase in the frequency of late frosts in some regions. Between 1975 and 2016, the frost risk for fruit trees (*Prunus* and *Malus*) in Switzerland increased at elevations above 800 m, while it remained unchanged at lower elevations. At elevations above 800 m, the phenological shift was strong, while the date of the latest spring frost did not change significantly (Vitasse et al., 2018). In the lowlands of Switzerland and Germany, the risk of damaging frost events did not change, as the earlier phenology was accompanied by an earlier occurrence of the last damaging frost in spring (Vitasse and Rebetez, 2018). However, in large parts of Europe, the amount of warming before the last frost date has increased over the last decades, indicating an increase in the risk of damage from late spring frosts (Zohner et al., 2020).

Several models addressed the development of bloom dates and frost risk in the future. According to model results, further advancement of the start of bloom can be expected (Bosdijk et al., 2024; Chmielewski et al., 2018; Hoffmann and Rath, 2013; Pfleiderer et al., 2019). However, the implications for further frost risk vary between regions and modeling approaches. Hoffmann and Rath (2013) predicted a decrease in frost risk for apple orchards in Lower Saxony (Germany) in the long run. In the Netherlands, the frost risk increased in the recent past, but is expected to decrease with ongoing climate change (Bosdijk et al., 2024). A similar reduction in future frost risk is expected for Trentino (Italy) (Eccel et al., 2009). In contrast, Pfleiderer et al. (2019) modeled the frost risk in German fruit growing regions under a 2°C warming scenario compared to the recent past, with the results indicating an increase in frost risk for most regions (Pfleiderer et al., 2019). The future frost damage frequency for cherries and sloes differs across geographical locations and species, with some regions expecting increased frost damage, while others may see a decrease (Ma et al., 2019). In general, it can be expected that late spring frost will continue to pose a challenge for fruit production by the end of the century (Chmielewski et al., 2018; Eccel et al., 2009).

Despite the clear trend towards earlier blossom, some studies describe a delayed fulfillment of chilling requirements for apple trees in the future (Hoffmann and Rath, 2013; Pfleiderer et al., 2019). In particular, for southern Germany, there is a risk that chill requirements may no longer be met before spring, potentially affecting bud development and flowering (Pfleiderer et al., 2019).

Outside of Europe, changes of phenology and frost risk are also being observed. Ru et al. (2023) showed that in the Loess Plateau of China, budburst and fruit set in apple are expected to occur earlier under several future climate scenarios. While most scenarios project a decrease in frost frequency, they also indicate an increase in frost intensity (Ru et al., 2023). Chen et al. (2024) predicted an advancement of spring phenology accompanied by increasing frost risk in northern China, whereas in the southern regions, delayed phenology and a decrease in frost risk are expected. In Japan, an earlier onset of phenological stages is projected. However, the strength and impact of these changes on frost risk vary depending on the region, the climate model used and the specific future time horizon considered (Masaki, 2020).

1.5 Modeling orchard systems

Modeling has a long-standing tradition in orchard-related horticultural research and is used to address a wide range of topics. One of the key advantages is the ability to integrate knowledge across different scales - from the molecular level to orchard scale – allowing researchers to test whether conceptual frameworks are coherent and to identify gaps in current knowledge (DeJong, 2019).

1.5.1 Yield prediction

In recent years, a variety of analytical models have been developed to predict the yield of apple orchards. These models utilize input from ground based RGB images (Aggelopoulou et al., 2011; Cheng et al., 2017), LiDAR measurements (Gené-Mola et al., 2020) or satellite images (Bai et al., 2021). Additional parameters such as morphological characteristics (Bharti et al., 2023) and soil properties (Papageorgiou et al., 2013) also contribute to yield predictions. A common approach involves neural networks (Bharti et al., 2023; Cheng et al., 2017; Črtomir et al., 2012), but other technologies, such as Fuzzy Cognitive Mapping (Papageorgiou et al., 2013), reflectance thresholding, Support Vector Machines (Gené-Mola et al., 2020), random forest modeling and the Carnegie–Ames–Stanford approach (Bai et al., 2021) are also applied successfully.

1.5.2 Phenology modeling

Temperate fruit trees, such as stone fruits, require the fulfillment of both chill and heat requirements during the dormancy phase to ensure proper flowering in spring (Fadón et al., 2020). Over time, a broad range of models has been developed to describe chill accumulation. Some of the most well-known modeling concepts include the Chilling Hours Model (Weinberger, 1950), the Utah model (Richardson et al., 1974) and the dynamic model (Fishman et al., 1987a, 1987b). For modeling heat accumulation, the most widely used approach is the Growing Degree Hours (GDH) Model developed by Anderson et al. (1986). More recently, PhenoFlex, a process-based model introduced by Luedeling et al. (2021) integrates the dynamic model and the GDH model to improve predictions of spring phenology.

1.5.3 Economic models

Various economic models are available for analyzing decision at different scales, ranging from farm-level to country wide economic questions. Deterministic cost-benefit models support fruit growers make informed investment decisions, such as evaluating the feasibility of different multi-purpose apple harvesting platforms (Zhang et al., 2019). Optimization models can assist in scheduling the apple harvest to maximize the quantity of marketable fruits, while minimizing resource use (González-Araya et al., 2015) or in planning the optimal mix of apple varieties for a farm (Willis and Hanlon, 1976). At a larger scale, Tozer and Marsh (2018) developed an intertemporal model of apple demand and supply for the US apple marked and Wani and Mishra (2022) proposed a circular economy model aimed at increasing sustainability in Indian apple production.

1.5.4 Apple production related probabilistic modeling

Probabilistic modeling approaches are used in various contexts related to apple production. For example, they have been frequently used to assess consumer exposure to pesticide residues, such as chlorpyrifos (Ferrier et al., 2006) and captan (Zentai et al., 2013) resulting from apple consumption. Uljas et al. (2001) applied probabilistic modeling to compare methods for reducing *E. coli* O157:H7 populations in unpasteurized apple cider. Beyond food safety, these techniques have been used to model light transportation within apple fruits (Askoura et al., 2015) and to conduct life cycle assessments of post-harvest apple supply chains (Michiels and Geeraerd, 2022). In economic context, Chalgynbazeva et al. (2024) explored the potential of agriphotovoltaic systems in Hungarian apple production. Similarly, Uçar et al. (2016) evaluated the economic viability of investing in an apple orchard in Slovakia, while Simbürger et al. (2022), compared hail and frost insurance systems with a proposed system for tax-exempted provisions for apple producers in Austria, using probabilistic modeling techniques.

1.6 Decision analysis and probabilistic forecasts

Life as a fruit grower is marked by a high degree of uncertainty. Growers have to navigate a range of unpredictable natural influences, such as weather extremes and plant pathogens, while also considering fluctuating economic circumstances like fruit market prices and labor costs. Furthermore, the legal and regulatory framework (e.g. allowed plant protection products or minimum wages) is subject to change over time. Nevertheless, the flexibility in fruit production is comparatively low. Once fruit trees are planted, they typically require four years to reach full productivity and remain in production for approximately 18 years. Further investments in infrastructure, such as irrigation, frost protection or storing facilities are often long-term commitments, that often tie up capital for many years. As a result, fruit growers are frequently required to make critical management and investment decisions under considerable uncertainty. One valuable tool to support them in these complex choices is decision analysis.

Decision analysis is a structured, mathematical approach designed to support decision-making under conditions of uncertainty (Muenning, 2017). It can be applied in situations where choosing between two or more options entails irrevocable consumption of resources (Howard and Abbas, 2015) and potential long-term consequences. This method helps to rationalize complex and risky decisions, providing decision-makers with a clearer understanding of the trade-offs involved and the implications of their actions (Anderson, 1977; Howard and Abbas, 2015). A core principle of decision analysis is to incorporate all elements relevant to the decision, drawing from a wide range of information sources, including experts, stakeholders, and the decision-makers themselves (Luedeling and Shepherd, 2016). Beyond its structured format, decision analysis promotes a comprehensive and transparent view of the decision at hand, encouraging informed, reflective, and accountable choices.

In brief, the methodology to develop a decision model typically follows a structured sequence of steps (Figure 4). To ensure that the model reflects real-world complexities and priorities, experts, stakeholders and decision makers are integrated into the modeling process from the outset through collaborative workshops (Whitney et al., 2018). These workshops form the foundation for creating a transdisciplinary decision model, which is designed to incorporate risks and uncertainty through probabilistic simulation (Luedeling and Shepherd, 2016). A possible framework to implement decision models and to make probabilistic projections based on Monte Carlo sampling is the *decisionSupport* R package (Luedeling et al., 2022). Monte Carlo simulations generate a large number of independent random numbers based on predefined probability distributions (Bonate, 2001). The specification of these distributions — such as the range and type of distribution — should be informed by the best available evidence, including inputs from calibrated experts (Shepherd et al., 2015). Calibrated experts, are individuals who have undergone training in making well-calibrated and statistically sound estimates (Hubbard, 2014; Whitney et al., 2024).The results of Monte Carlo simulations not only support decision-making under uncertainty, but can also be used for further analyses, such as Variable Importance in Projection (VIP) (Luedeling and Gassner, 2012) or the Expected Value of Perfect Information (EVPI) (Hubbard, 2014; Lanzanova et al., 2019).

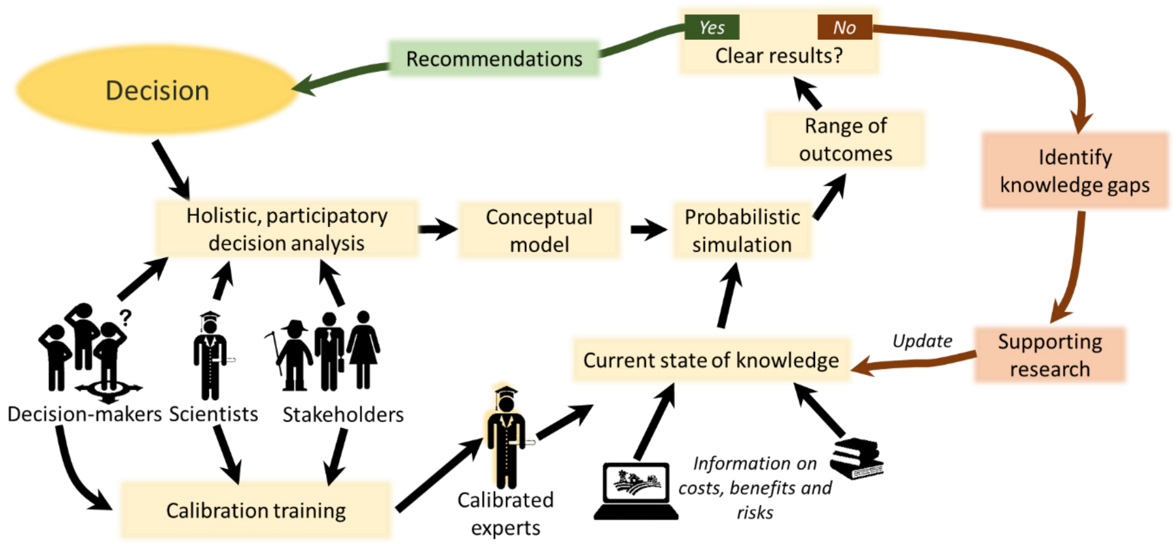

Figure 4: Decision analysis workflow: Decision-makers, scientists and stakeholders take part in a participatory process to develop the decision model. The researcher translates the model into a probabilistic simulation. The inputs values are set, based on all available sources of information, including estimates by calibrated experts. The simulation produces ranges of outcomes. If the results are not clear, EVPI analysis can be used to identify important variables and knowledge gaps to indicate where supporting research is useful. Figure source: INRES Horticultural Sciences, adapted from Luedeling and Shepherd (2016)

In horticulture, decision analysis has been recently applied to support investment decisions and management strategies. For example, Rojas et al (2021) applied decision analysis to assess the viability of investing in plastic covers to protect sweet cherry orchards in Chile from extreme weather events. Similarly, Ruett et al. (2020) utilized decision analysis to evaluate and compare different management strategies in ornamental plant nurseries.

1.7 Research objectives

Every year, fruit growers are confronted with many uncertainties – ranging from of environmental factors such as weather and pests to economic variables such as the apple prices – while striving to produce high-quality fruit. To support fruit growers in their short and long-term planning, modeling tools to rationalize decisions are a useful contribution. Although a yield and quality assessment several weeks before harvest would be of great benefit for growers and marketers, there is currently no yield prediction model that adequately incorporates local conditions, especially pests, diseases, hail events, late frost risk and water availability. Therefore, the first objective of this work was to adapt the decision analysis approach to develop a probabilistic model capable of predicting total apple yield and high-quality yield at harvest. This model is intended to be applicable as early as possible during the growing season to support timely decision-making (Chapter 2).

One major risk in fruit production is the occurrence of late spring frosts, which can damage buds, flowers or young fruits and may cause severe yield losses and reduced fruit quality. Since fruit growers all over Germany depend on reliable information about local frost risk to make informed management decisions, the second objective of my research was to analyze historic and current phenology and temperature data to identify regional patterns and trends in spring frost occurrence in Germany. To make the results easily understandable and accessible to fruit growers, advisors and scientists, I created raster maps visualizing the historical frost frequency of spring frost events (Chapter 3). As late spring frosts occur in all important German fruit growing regions, many growers are considering investments in frost protection measures and seek guidance on which method is most suitable and economically viable. However, most existing economic comparisons of frost protection measures do not adequately account for uncertainties in input values especially the highly variable frequency of frost events. The third objective of my research was therefore to apply the strengths of the decision analysis modeling approach, specifically its capacity to incorporate uncertainty, variability and risks – into an economic comparison of active frost protection measures versus production without protection. I developed a model comparing the economic outcomes of using paraffin candles, below-canopy irrigation, mobile wind machines and stationary wind machines, which only considered the phase of mature apricot trees (Chapter 4).

Over the course of the study, the initial, simplified model evolved into a more comprehensive decision-support tool that covers the entire lifetime of an orchard. This expanded model includes a wider range of frost protection measures: overhead and below-canopy irrigation, mobile and stationary wind machines, tractor-mounted and portable gas heaters, candles and pellet heaters. I applied this model to apple orchards in two major growing regions, the Rhineland and the Lake Constance region (Chapter 5). As frost protection is of crucial economic importance for fruit growers, the model predictions provide valuable insights to support fruit growers in making more informed investment decisions.

Throughout my studies, scientists, advisors as well as fruit growers expressed strong interest in predictions of future frost risk under changing climatic conditions. In response to this interest, I defined the estimation of future late spring frost risk for apples as my fourth objective. Using historical data (see Chapter 3) and the PhenoFlex phenology model, I predicted the probability of frost events for the years 2050 and 2085 under various climate scenarios (Chapter 6).

Overall, the aim of this thesis was to apply scientific modeling techniques - including, decision analysis, process-based phenology modeling and Kriging interpolation - to address practically relevant questions in fruit production. The results are intended to support advisors and farmers to make informed decisions while explicitly accounting for uncertainty.

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Chapter 2: ProbApple – A probabilistic model to forecast apple yield and quality

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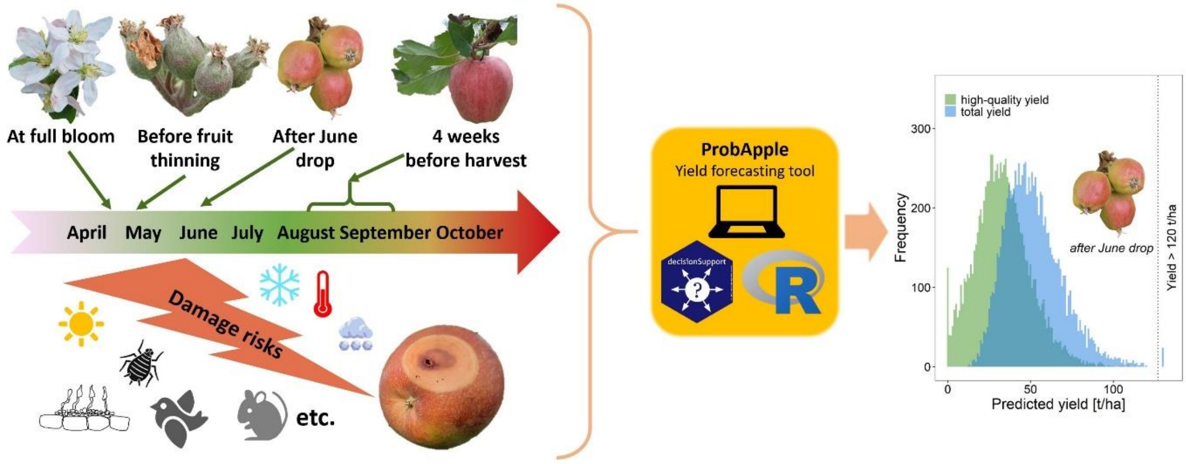
Graphical Abstract



Highlights

- ProbApple enables the forecast of apple yield and high-quality yield.
- Natural variability and uncertainty are included in the calculation.
- The model can be customized for different apple varieties and growing regions.
- Results show the positive influence of anti-hail netting on high-quality yield.
- ProbApple can support fruit growers in their short- and long-term planning.

Abstract

CONTEXT: Fruit yield and quality are critical determinants of the economic performance of apple orchards. However, these economic metrics are highly uncertain due to various quality-reducing factors during the growing season, and fruit growers would greatly benefit from reliable predictions.

OBJECTIVE: In this study, we aim at developing a new tool to support fruit growers in anticipating yield and potential quality losses under the specific conditions of their orchards. The tool should allow application at four key time points during the growing season (at full bloom, before fruit thinning, after June drop, and four weeks before harvest) and capture uncertainty in the quality-reducing factors and the resulting yield parameters.

METHODS: apple yield for a 'Gala' orchard in the German Rhineland. We compared scenarios with and without anti-hail netting to demonstrate the use of the model for predicting apple yield.

RESULTS AND CONCLUSIONS: Applying the model four weeks before harvest, the median forecasted apple yield was 50.4 t/ha (25%-quantile: 44.0; 75%-quantile: 57.8 t/ha) with anti-hail netting and 49.3 t/ha (25%-quantile: 42.7; 75%-quantile: 56.5 t/ha) without. The forecasted high-quality yield was 34.9 t/ha (25%-quantile: 27.5; 75%-quantile: 41.6 t/ha) with the protection measure and 30.0 t/ha (25%-quantile: 15.8; 75%-quantile: 38.7 t/ha) without. These results are in line with commonly achieved 'Gala' apple yields in the Rhineland region.

SIGNIFICANCE: We show that ProbApple is a customizable tool for forecasting apple yield and quality, offering producers valuable insights for operational planning and informed management decisions.

1. Introduction

Fruit quality, along with overall yield, is a key determinant of fruit growers' incomes, as it affects the fruits' overall marketability and price (Badiu et al., 2015; Carew, 2000). External quality parameters such as size or color attract consumers to buy the fruits, whereas internal quality parameters such as taste influence the probability of repeat purchases (Khan et al., 2019). Apple quality is influenced by a number of environmental, genetic and agronomic factors (Musacchi and Serra, 2018). Among the environmental factors are extreme weather events, including late spring frosts (Rodrigo, 2000; Schmitz et al., 2025) and hail (Rana et al., 2022), as well as biotic agents such as birds (Anderson et al., 2013), fungal diseases or insects. Depending on the variety, physiological disorders such as bitter pit are a challenge in apple production (Jemrić et al., 2017). Many agronomic measures aim at improving fruit quality either through permanently installed protective devices such as anti-hail netting or overhead irrigation, or through management steps like summer pruning and pneumatic defoliation to enhance fruit coloration (Andergassen et al., 2023; Kiprijanovski et al., 2016; Snyder and Melo-Abreu, 2005).

Due to the variability of environmental factors, apple yield and quality are highly uncertain. Since yield and quality greatly impact the effort needed in harvesting and marketing, fruit growers would benefit from tools that allow reliable yield and quality predictions. For this reason, researchers have been developing modeling tools to predict apple yield or quality for at least six decades. Batjer et al. (1957) predicted the fruit size at harvest of 'Delicious' and 'Winesap' apples, based on its correlation to the fruit size at several time points during the vegetation period (every 5 days from 35 days after full bloom until harvest). Winter presented his well-known, comprehensive model for predicting apple yield in 1969. This model was based on statistical data, regional and variety-specific characteristics, and estimates of fruiting density and fruit size (Winter, 1969). He later developed his modeling approach further and published the FURPRO model, which computes yield and several economic parameters for apple orchards (Winter, 1986). More recently, modern modeling approaches have been tested in an effort to predict the yield at harvest. Bharti et al. (2023) employed an artificial neural network to forecast apple yield based on morphological parameters, such as plant height and fruit set. Aggelopoulou et al. (2011) processed images of apple trees at bloom to forecast yield, and Hester and Cacho (2003) presented a deterministic biophysical model for apple yield prediction. However, few models address fruit quality, and if so, they typically focus on a single parameter such as the fruit size at harvest (e.g. Forshey, 1971; Marini et al., 2019; Stajnko et al., 2013), or the damage caused by codling moths (Martin et al., 2014). More critically, none of the models address the high variability in the factors affecting fruit quality and quantity and the resulting uncertainty in the projections. One approach that is well suited to accounting for uncertainty is decision analysis.

Decision analysis approaches are widely used across various business and research fields to formulate knowledge-based recommendations for decision-making (Luedeling and Shepherd, 2016). By repeatedly sampling from probability distributions that account for both variability and uncertainty in the variables influencing the decision recommendation, this method effectively propagates these uncertainties and variabilities to the model projections. The input distributions can be derived from available data as well as from expert knowledge. In recent years, decision analysis has been introduced into horticultural research, for example to evaluate management strategies in ornamental plant nurseries (Ruett et al., 2020) or to assess the viability of using plastic covers to protect cherry orchards in Chile (Rojas et al., 2021). In general, decision analysis is a useful technique to model interactions in complex systems, which are common in agroecological systems (Whitney et al., 2023) such as apple orchards.

We adapted the decision analysis approach to develop a probabilistic model that predicts total and high-quality yield at harvest. Our modeling procedure incorporates uncertainty regarding inputs and outputs and can be adapted for different cultivars and growing regions by adjusting the input estimates. We illustrated the functionality of the model using a case study of 'Gala' apple production in the German Rhineland.

2. Materials and methods

The general workflow in decision analysis includes four major steps: (i) involving experts and stakeholders in building the conceptual model, usually through expert workshops, (ii) implementing a simulation model, (iii) gathering estimates for model parameters from experts or other sources, and (iv) conducting Monte Carlo simulations to make predictions.

2.1. Model development

2.1.1. Expert Workshop

We reached out to 32 apple production experts, equally representing science, fruit-growing advisory services and practice. After checking their availability and willingness to take part in an expert panel, thirteen apple production experts were recruited to contribute to the model building process, including 6 scientists, 3 fruit growing advisors, 2 apple growers and 1 agricultural meteorologist. The composition of the panel ensured that all relevant topics were well covered by the experts. In a participatory online workshop held in May 2022, the following questions were addressed: Q1: "*How do we define quality yield (quality parameters)*?", Q2: "*What influences the quality parameters*?" and Q3: "*When does the forecast make sense (time in the growing season)*?". The questions were chosen to facilitate systematic development of the conceptual model in terms of target variables (Q1), input variables (Q2) and temporal resolution of the model (Q3). We classified the quality-influencing parameters according to the time of their occurrence during the year. The aim of the workshop was to develop a conceptual model which represents the modelled system. We followed the main steps of conceptual model development, which include defining the context (quality parameters), identifying key factors and mapping the relationships between the model elements (influences on quality) (Pace, 2000). In order to elicit all relevant information from the experts, we employed a three-step group knowledge elicitation process, as described by Whitney et al. (2018), and adapted it for an online workshop. After the participants were afforded time for individual reflection, they were asked to share their ideas with a randomly selected partner in a breakout session. Finally, we collected the ideas in three moderated sessions with three to four experts.

After the workshop, we consolidated the results from the three sub-groups into joint lists of factors by compiling all responses, removing duplicates and merging similar answers. The list of quality parameters was expanded with further parameters listed in the EU marketing standards for apples (European Commission, 2004). We grouped the quality parameters into external, internal, and other quality parameters, presenting them as a tree diagram (Supporting information 4). We grouped the influencing factors into fixed factors (related to location, orchard and long-term management), positive influences, negative influences and factors with both positive and negative potential effects on apple quality. These were mapped to a timeline to illustrate their occurrence throughout the year (Supporting information 5). Reliability was ensured through an iterative process during the workshop, a plausibility check during result consolidation, and a feedback round on the final diagrams (Supporting Information 4 & 5).

2.1.2. Simulation Structure

Based on the workshop results, we developed a model to forecast apple yield and quality at harvest. The model was implemented in the programming language R (R Core Team, 2024) using functions from the packages *decisionSupport* (Luedeling et al., 2024) and *tidyverse* (Wickham et al., 2019). The plots created with *ggplot2* (Wickham et al., 2022) were enhanced with the use of *patchwork* (Pedersen, 2022), *ggtext* (Wilke and Wiernik, 2022) and *png* (Urbanek, 2022).

We used the BBCH scale (scale for plant growth stages, named after the institutions which developed it: Biologische Bundesanstalt (German Federal Biological Research Centre for Agriculture and Forestry), Bundessortenamt (German Federal Office of Plant Varieties) and Chemical Industry), to describe the forecasting time points. The BBCH scale for pome fruit was developed by Meier et al. (1994). ProbApple can be used at four time points during the growing season:

1. At full bloom (BBCH 65): Early forecasting time covering the whole fruit development and ripening period.
2. Before fruit thinning (BBCH 71-72): The fruitlets have a diameter of approximately 10 mm and most unpollinated flowers have been shed. The model user can obtain a first impression of fruit set in the orchard.
3. After June drop (BBCH 74): June drop is a natural fruit shedding period that occurs six to eight weeks after blossom, during which mainly fruits with few or poorly formed seeds drop down (Link, 2011). After this drop period, the number of apples per tree can be reliably estimated. Knowledge about yield and quality at harvest can assist farmers in planning the harvest (e.g. organize labor, and procure storage boxes) and retailers in organizing their purchases.
4. Four weeks before the estimated harvest date: Fruit diameter increase slows down and the ripening process sets in. Nevertheless, risks continue to threaten harvest success. Farmers can use yield and quality forecasts for detailed harvest planning. To define this time point, we used the estimated harvest time provided by the local extension service, which is based on time after full bloom and time after T-stage (BBCH 74, underside of fruit and stalk forming a ‘T’, transition between the cell division and cell elongation phases (Büchele, 2018)).

The model is structured according to these four periods, which describe the fruits’ growth and ripening process. It consists of two sub-models (Figure 1): One sub-model focuses on apple quantity, i.e. yield per ha, while the other one predicts apple quality. The quality sub-model considers the visual appearance of the apples; internal quality parameters such as sugar content are not part of this model. To forecast apple yield and quality at harvest, the models were combined to create a single model, which was then used for Monte Carlo simulations.

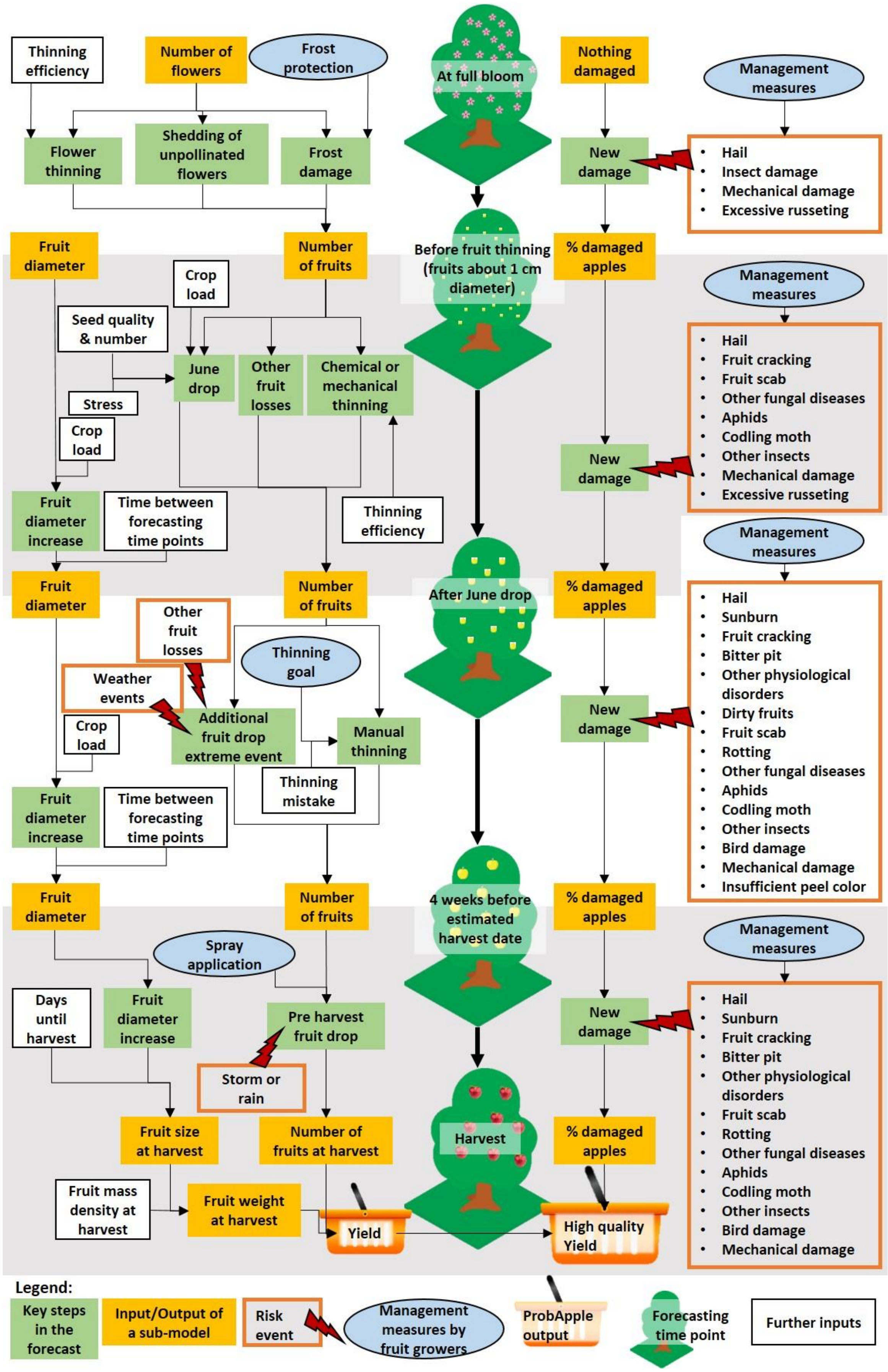


Figure 1: Simplified model structure of the ProbApple model. The model can be used at four time points, represented by the trees in the diagram: at full bloom, before fruit thinning, after June drop, four weeks before the estimated harvest date.

We assume that plant protection and weed control are carried out according to standard practices in 'integrated production' with average success. Other management options can be selected when running the model. We implemented the following management options:

1. Frost protection: Overhead irrigation to protect buds and flowers from damage by late spring frost.
2. Pollinator support: Measures to promote wild bees, honeybees or bumblebees in the orchard to improve pollination.
3. Chemical flower thinning: Spraying of chemicals such as ammonium thiosulfate or 2-chloroethylphosphonic acid (Ethephon) to lower the number of viable flowers and reduce fruit set.
4. Mechanical flower thinning: Use of a string thinner which removes or damages flowers, flower clusters, leaves and small branches to reduce fruit set.
5. Chemical fruit thinning: Spraying of chemicals such as ammonium thiosulfate, 2-chloroethylphosphonic acid (Ethephon) or 1-naphthaleneacetic acid to increase fruit drop.
6. Manual thinning after June drop: Manual removal of apples, mainly visibly damaged fruits and fruits from clusters with more than two fruits.
7. Anti-hail net: Protecting the trees against hail damage by installing a net above the trees. Anti-hail nets can increase problems with peel color, but decrease the risk of sunburn.
8. Irrigation: The trees receive supplemental water through a drip irrigation system to avoid drought stress.
9. Foliar fertilization: Foliar fertilizers such as calcium are sprayed on the leaves. This can reduce quality problems such as bitter pit.
10. Climatizing irrigation: Using the overhead irrigation in summer helps to reduce sunburn problems on hot and sunny days.
11. Spraying of kaolin: Additional measure to reduce sunburn.
12. Summer pruning: Pruning of the apple trees in summer exposes apples to additional light, leading to improved peel coloring. This measure can raise the risk of sunburn.
13. Removing leaves: Some leaves of the apple tree can be removed with a pneumatic leaf remover a few weeks before harvest. Sunburn problems slightly increase.
14. Spraying against preharvest fruit drop: Spray application of growth regulators to reduce preharvest fruit drop. This is usually not done in 'Gala' apple production.

2.1.3. Simulation outputs

The yield module of the simulation provides forecasts of the average fruit diameter and the mean number of fruits per tree. From the fruit diameter (d) and an estimate of the apples' volumetric mass density (ρ, mass (g) per volume (cm^3)) at harvest, the model calculates the fruit weight, approximating the shape of the apple by a spherical shape. Fruit weight and fruit number (n) are multiplied to estimate the total yield at harvest (Equation 1).

$$total\ yield = n * \left(\left(\frac{4}{3} * \left(\frac{d}{2}\right)^3 * \pi\right) * \rho\right) \text{(Equation 1)}$$

The quality module of our model forecasts the percentage of damaged apples at harvest. The model then computes the high-quality yield as the share of apples that can be marketed as dessert apples.

If the model runs from the forecasting time points 'at full bloom', 'before fruit thinning' or 'after June drop', it also returns intermediate results for the mean number of fruits per tree and the percentage of damaged apples at all forecasting time points later in the season. The model code and simulation results of our case study (Supporting Information 1 & 2) are available on GitHub and Zenodo (Schmitz et al., 2024)

2.1.4. Model parametrization

To gather values for all input variables, we used literature and expert knowledge. To prepare all participating experts for the model parametrization session, they were subjected to calibration training to enhance their ability to make accurate estimates. Calibration training, inspired by Hubbard (2014), consists of providing participants with information on cognitive biases (e.g. the Dunning-Kruger effect (Kruger and Dunning, 1999), and the Anchoring effect (Kahneman, 2011)), instructing them in techniques to improve estimation skills (Equivalent bet (Hubbard 2014), Klein's premortem (Klein, 2008), Start with unreasonably wide distributions), and supporting them in practicing these skills using trivia questions. Through several rounds of such questions, each followed by feedback on the accuracy of the estimates, most participants markedly increase their estimation skills. ProbApple needs all input parameters (except of the constant values) in the form of 90% confidence intervals, which is typical for Monte Carlo simulations based on the decision analysis methodology (Hubbard, 2014). After calibration training, the experts estimated model input values in the form of lower and upper bounds of 90% confidence intervals and defined the type of distribution for each variable (Supporting Information 1). To generate estimates for all input parameters, two types of estimates were used: i) estimates based solely on expert knowledge and ii) estimates based on experimental data and literature as a knowledge base without a formal analysis. The estimates were discussed in the expert group during the workshop to ensure reliability. To apply the model to a specific orchard, the user must provide estimates for several input parameters, including the number of trees per hectare and the number of flower clusters or fruits at the prediction time point. These inputs should be submitted in the form of a csv-file.

For the time points 'before fruit thinning', 'after June drop' and 'four weeks before harvest' an estimate of the percentage of visibly damaged apples is needed. The last two forecasting time points require an estimate of the fruit diameter at the prediction time point. If trees are still young, the variables *lower bound of the optimum range of number of apples per tree* and *width of the optimum range of number of apples per trees* should be adjusted. Like the general inputs, the orchard-specific parameters must also be specified as 90% confidence intervals. To use the model in regions with different growing conditions or for other varieties, the user can check all input parameters and adjust them, by providing their own confidence intervals (Supporting information 3). This allows, for example, customizing the model with location-specific weather risk estimates. Management measures that are applied in the orchard also need to be specified.

2.1.5. Probabilistic simulation

We ran Monte Carlo simulations with 10,000 realizations to estimate yield and fruit quality at harvest. This high number of realizations assured smooth and coherent result distributions. In each realization, a random sample is drawn from the input parameter distributions and used to calculate the model results. We combined all realizations into a distribution of outcomes representing the uncertainty in the simulation results.

We further analyzed the model and the simulation results to identify influential input variables. To evaluate the influence of each variable on the high-quality yield, we performed a sensitivity analysis using Partial Least Squares (PLS) regression. The values sampled from the input distributions during the Monte Carlo simulation served as the independent variables (regressors), while the forecasted high-quality yield was the dependent variable (regressand) in the PLS-regression. The analysis was conducted for each forecasting time point separately.

We used the Variable Importance in the Projection (VIP) statistic with a threshold of 1 to identify the input variables that substantially affect the high-quality yield (Luedeling and Gassner, 2012). Mathematically, the VIP is a weighted sum of squares of the PLS weights (Wold, 1995). The weights describe how the input variables can be combined to represent a quantitative relation between the values drawn from the input table and the high-quality yield.

2.2. Case study

2.2.1. Apple variety

For the case study, we parameterized the model to predict yield and quality of 'Gala' apples in the Rhineland, an important apple growing region in western Germany (~6-8° E and ~49-51° N, Figure 2). 'Gala' is a well-established dessert apple variety produced on 9.6% of the German production area in 2022 (Destatis, 2022). It was originally bred in New Zealand as a cross between 'Kidd's Orange' and 'Golden Delicious' (Büchele, 2018). Several strains with different color characteristics are available (Guerra, 2017).

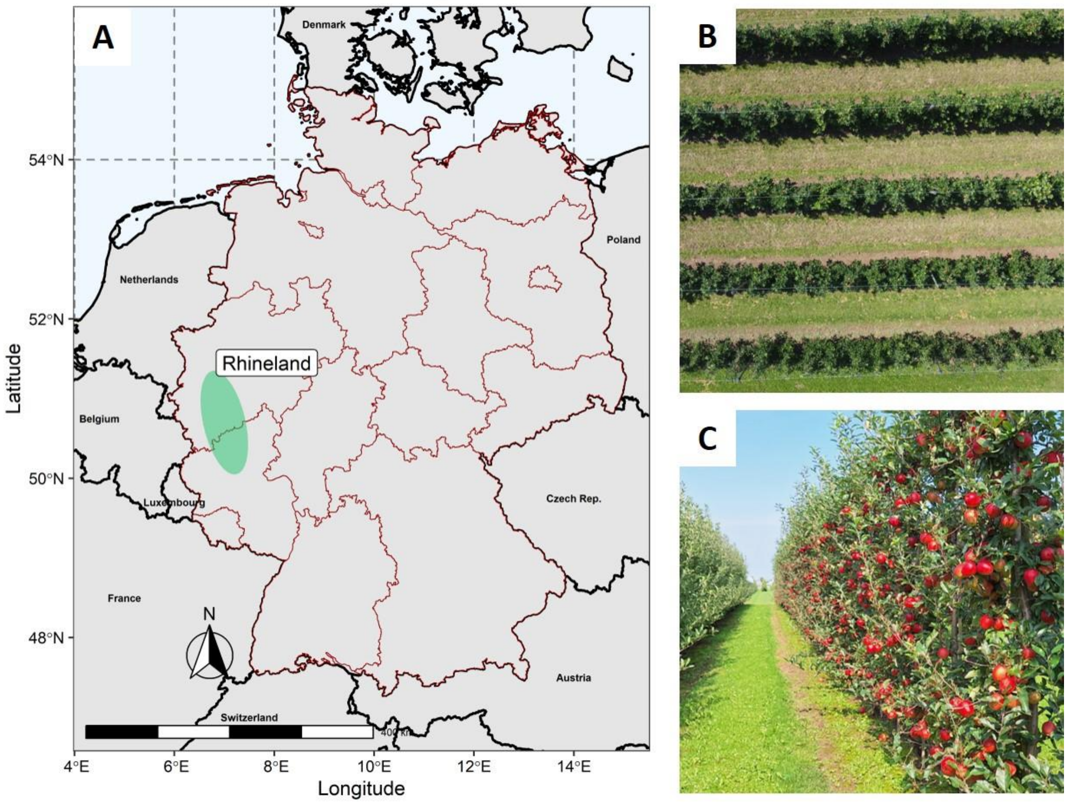


Figure 2: Information on the case study location and orchards. A) Map showing the location of the Rhineland region in Germany. Black lines show the national borders and red lines show the borders of the federal states in Germany. B) Drone image of the orchards at the research station in Klein-Altendorf (Rheinbach, Germany) taken on August 18, 2023. (Photo: Jan Ellenberger) C) Picture of a Gala Alvina row at the research station in Klein-Altendorf (Rheinbach, Germany) taken on September 5, 2024 (one day before harvest).

2.2.2. Management

We chose the management measures according to common practices in 'Gala' apple production in the Rhineland region (Table 1) and ran the model for two scenarios: with and without anti-hail net.

Table 1: Management measures in the model and their status in the case study.

Management option	Done
Frost protection	yes
Pollinator support	no
Chemical flower thinning	yes
Mechanical flower thinning	no
Chemical fruit thinning	no
Manual thinning after June drop	yes
Irrigation	yes
Foliar fertilization	yes
Climatizing irrigation	yes
Spray of kaolin	no
Summer pruning	no
Removing leaves	no
Spray against preharvest fruit drop	no

2.2.3. Estimates for the simulation

To show exemplary model results of forecasts at all four possible time points, we estimated a set of time point-specific input values (shown in Table 2). The number of trees per hectare was calculated based on the planting distance at the research station in Klein-Altendorf (Rheinbach, Germany), which is 1 m x 3.2 m. Estimates for numbers of flower clusters and fruits were provided as an example and validated through a reality check by randomly counting flower clusters and fruits on selected trees in the orchard.

3. Results

3.1. Workshop results

Overall, the experts showed high interest in collaborating on the workshop questions. Several important quality parameters and influences were named in all sessions. Each sub-group contributed additional ideas, so that a holistic overall picture could be gathered. The resulting list contained a total of 79 factors influencing apple quality, covering the areas of management, environment, weather and risks during apple production.

3.1.1. Quality parameters

The experts listed apple quality parameters and divided them into three categories: 1) external quality, 2) internal quality, and 3) other quality parameters (Supporting Information 4). Most of the parameters are related to the marketing standard for apples in the European Union (European Commission, 2004). Experts also mentioned additional economic parameters such as the pack-out, horticultural parameters such as the avoidance of alternate bearing and nutritional parameters such as sugar content. Our model focuses mainly on the external quality at harvest time in order to describe the marketability as a dessert apple. Parameters identified as most important for describing external quality are fruit color, fruit size and the absence of damage. Additionally, apples should be healthy and meet the characteristics of the variety.

Table 2: Estimates for our case study to forecast yield and quality in a 'Gala' apple orchard. We provide the lower and the upper bound of 90% confidence intervals. The distributions are posnorm = generally normally distributed, but only positive values are possible, const = constant, and tnorm_0_1 = truncated normal distribution with values between 0 and 1. The time points are tp1 = at full bloom, tp2 = before fruit thinning, tp3 = after June drop, tp4 = four weeks before the estimated harvest date.

Variable	distribution	lower	upper	unit
Fruit diameter at tp3	posnorm	2	3.5	cm
Fruit diameter at tp4	posnorm	5.9	6.5	cm
Lower bound of the optimum range of number of apples per tree	posnorm	70	80	apples
Mean number of flower clusters at tp1	posnorm	70	300	clusters
Mean number of fruitlets per tree at tp2	posnorm	80	600	apples
Mean number of fruits per tree at tp3	posnorm	80	140	apples
Mean number of fruits per tree at tp4	posnorm	75	120	apples
Number of trees per ha at tp1	const	3125	3125	trees/ha
Number of trees per ha at tp2	const	3125	3125	trees/ha
Number of trees per ha at tp3	const	3125	3125	trees/ha
Number of trees per ha at tp4	const	3125	3125	trees/ha
Percentage of visibly damaged apples at tp2	tnorm_0_1	0.025	0.1	%/100
Percentage of visibly damaged apples at tp3	tnorm_0_1	0.1	0.15	%/100
Percentage of visibly damaged apples at tp4	tnorm_0_1	0.1	0.2	%/100
Width of the optimum range of number of apples per trees	posnorm	30	40	apples

3.1.2. Influences on fruit quality

Apple quality is not only influenced by conditions during the vegetation period (Supporting Information 5). Fixed factors such as the growing location or variety form the initial situation. Additionally, influences from the previous year (e.g. harvesting technique) and the winter (e.g. chill accumulation) play a role in quality development. The main focus of the model, however, is on the events during the vegetation period. The experts highlighted various risks that may damage the developing apple fruits, e.g. weather-related risks such as hail, as well as the risk of damage by insects (e.g. apple codling moth, *Cydia pomonella*), physiological disorders or fungal diseases (Supporting Information 5). Furthermore, they listed management measures that fruit growers take to protect their orchards and to enhance fruit quality (e.g. frost protection, thinning and hail protection).

3.1.3. Forecast time points

Initially, the experts envisioned a model that could be used at all times between bloom and harvest. Ideally, such a model should also be able to provide management recommendations, e.g. related to thinning. Upon further reflection, however, the experts agreed that a model that focuses on certain crucial moments in the production cycle would be more realistic and serve most of the intended purposes. From the experts' point of view, the most interesting time point for forecasting is after June drop. At this point, some risks, such as the risk of frost, are no longer relevant, and chemical and mechanical thinning as well as natural fruit drop are mostly over. A forecast after June drop is useful at farm level for organizing labor for harvest. Such a forecast may also inform retailers at the regional level about the expected production level of the current year. An earlier forecast, at full bloom, can be useful for anticipating the influence of various risk factors throughout the season. Shortly after bloom, when it is clear whether there has been a late spring frost or the orchard has problems with alternate bearing, a forecast could be helpful in deciding on a thinning strategy. Practitioners recommended adding another forecast date a few weeks before harvest, as this aligns with the end of the occurrence period of several risks and supports detailed planning for harvest and storage.

3.2. Case study

3.2.1. Total yield and high-quality yield

Applying our model to a 'Gala' apple orchard in the Rhineland, we forecasted a median number of fruits per tree between 89 (25%-quantile (Q25): 84, 75%-quantile (Q75): 93) in the forecast after June drop and 93 (Q25: 84, Q75: 102) four weeks before harvest. The widest range of 0 to 134 apples (median: 90, Q25: 86, Q75: 95) was forecasted at full bloom. These apples have a median average fruit diameter between 7.3 cm (Q25: 7.1 cm, Q75: 7.5 cm), forecasted four weeks before harvest, and 7.5 cm (Q25: 7.0 cm, Q75: 8.0 cm), forecasted before fruit thinning. This results in median total yield forecasts between 49.4 t/ha and 50.4 t/ha, when applying the model before fruit thinning and four weeks before harvest, respectively (Figure 3). In fifty percent of the model runs, the total yield forecasted before fruit thinning was between 39.6 and 60.3 t/ha. Four weeks before harvest, the uncertainty had decreased, resulting in a narrower range of 44.0 t/ha to 57.8 t/ha between the 25% and 75%-quantile. Depending on the time of the forecast, the model predicted median proportions of damaged apples between 26.7 % (Q25: 17.0 %, Q75: 46.3 %, predicted at full bloom) and 29.7 % (Q25: 20.4 %, Q75: 46.9 %, predicted after June drop). We forecasted a median high-quality yield between 32.1 t/ha after June drop and 34.9 t/ha four weeks before harvest. In half of the model runs, the forecasted high-quality yield lay between 21.7 and 43.1 t/ha after June drop and 27.5 and 41.6 t/ha four weeks before harvest (Figure 3).

3.2.1. Variable Importance in the Projection

Important variables in forecasting high-quality yield are the number of flower clusters or fruits per tree and the diameter of the apples at the forecasting time points (Figure 4). These variables, together with the weekly growth rates, have a strong positive influence on the high-quality yield. The variables *apple mass density at harvest*, which is used to assess the fruit weight based on the apple diameter, and *weekly diameter increase (tp4-harvest)*, representing the growth in the last time period, are relevant and positively correlated with the high-quality yield in the forecasts at all time points. Other positively correlated variables are the *number of flowers per cluster (tp1)* and the *percentage change of weekly diameter increase in case of overbearing* (crop load too high). The time spans between the forecast time points can be either positively or negatively correlated with the high-quality yield, depending on whether their use in the calculation leads to longer or shorter periods of high weekly diameter increase. The VIP analysis identified several problems in apple production that negatively impact the high-quality yield. These include damage by codling moths, other insects and rotting, as well as problems with the appearance of the apples, such as russeting and insufficient fruit color. Additionally, the *percentage of visibly damaged apples* four weeks before harvest, the *thinner efficiency in chemical fruit thinning (tp2-tp3)*, and the *drop rate of the first drop directly after blossom (tp1-tp2)* are influential variables with a negative correlation to high-quality yield (Figure 4).

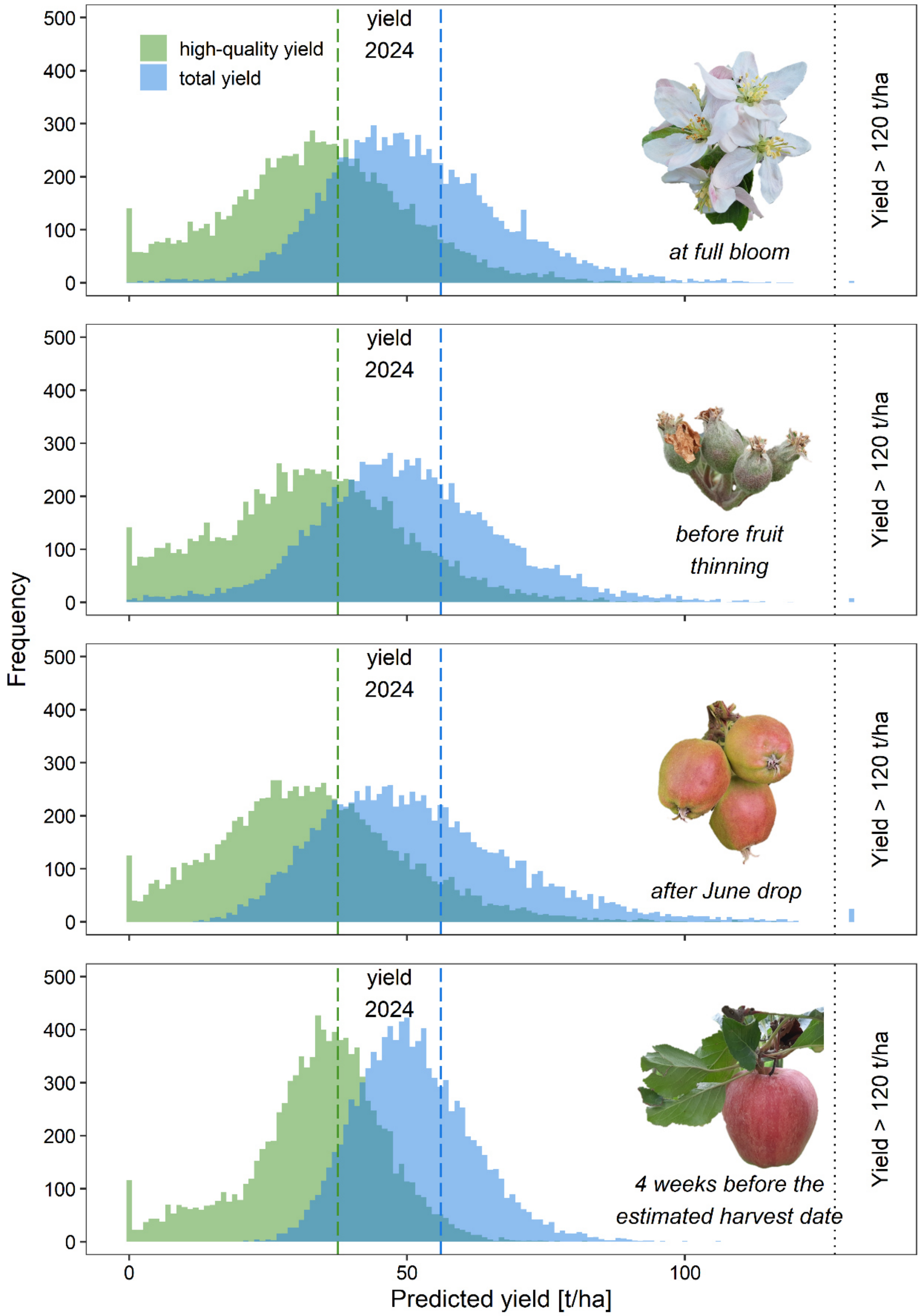
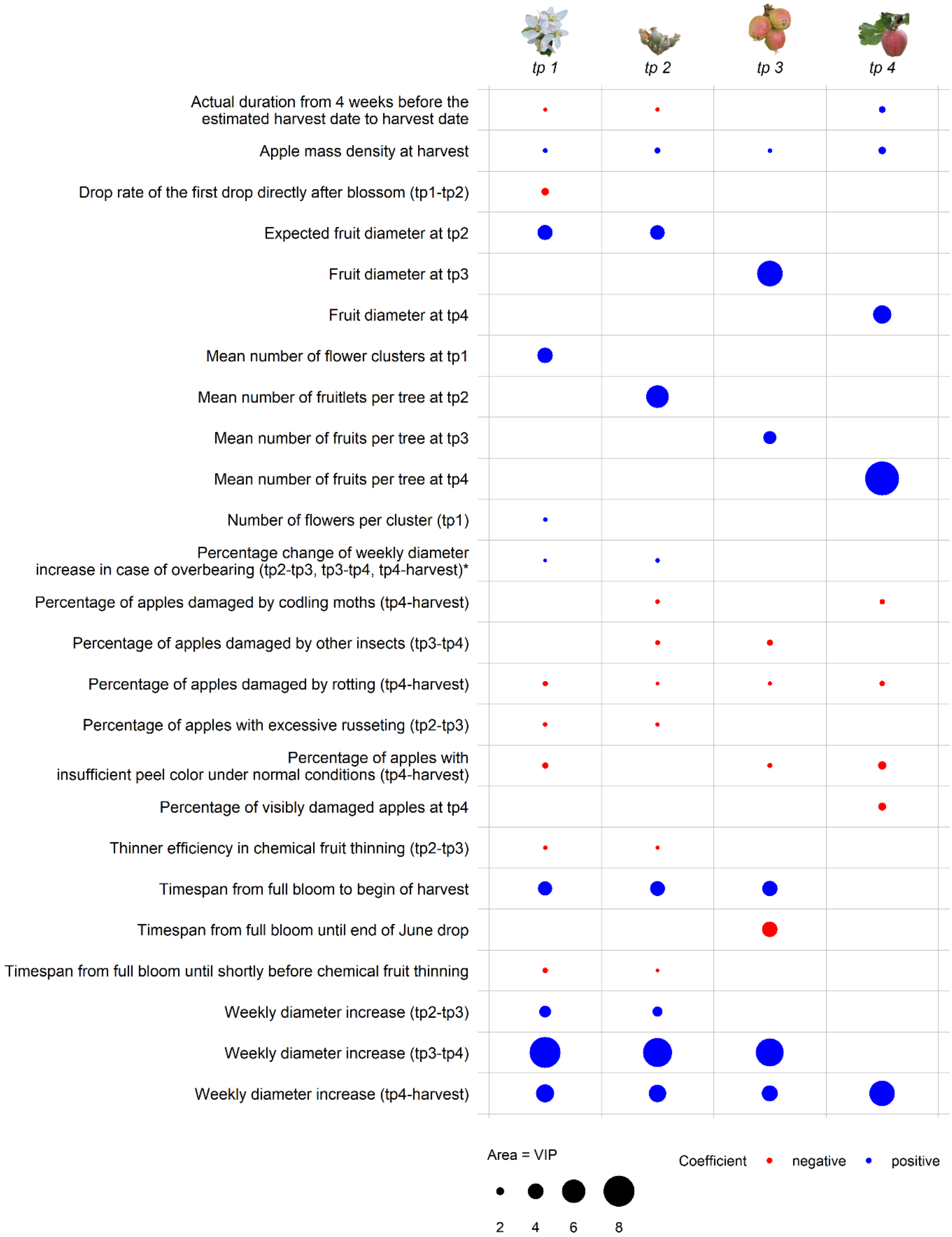


Figure 3: Frequency histograms of apple yield (total yield and high-quality yield) predicted at four time points throughout the year: at full bloom, before fruit thinning, after June drop and four weeks before the estimated harvest date. The histograms show the results of 10,000 Monte Carlo simulation runs. Forecasted yields above 120 t/ha are shown in a combined bin on the right side of the plot. Dashed lines show the observed total and high-quality yield in a Gala Alvina orchard in 2024 at the research station in Klein-Altendorf (Rheinbach, Germany).



*This variable has a negative value. A less negative i.e. higher value positively influences the high-quality yield, as the fruit growth is inhibited less strongly.

Figure 4: Variable Importance in the Projection scores of a Partial Least Squares regression model for the projection of the high-quality yield at harvest at four time points throughout the year: tp 1 = at full bloom, tp 2 = before fruit thinning, tp 3 = after June drop, tp 4 = four weeks before the estimated harvest date. The threshold for classifying a variable as important was set to 1. The dot size indicates the variable importance. Red dots indicate a negative and blue dots a positive correlation between the variable and the high-quality yield.

3.2.2. Influence of management options on high-quality yield

In most cases, the production of apples in an orchard without anti-hail netting leads to a lower high-quality yield compared to the production with anti-hail netting (Figure 5). While the most frequently predicted high-quality yield in the forecast at full bloom was 33 t/ha in an orchard with anti-hail net, the most frequent forecast in the scenario without anti-hail net was 8 t/ha. Similar results were found at the forecast time points before fruit thinning and after June drop. Only at the last forecasting time point, the most frequently predicted high-quality yield was 34 t/ha in both scenarios. Outcome distributions for high-quality yield with anti-hail netting are more or less symmetrical, while the outcome distributions for high-quality yield without anti-hail netting are right-skewed at the forecast time points 'at full bloom', 'before fruit thinning' and 'after June drop', but bimodal 'four weeks before harvest'. Without anti-hail netting, the median number of fruits per tree and the median total yield are slightly lower than in an orchard with anti-hail netting. In addition, more fruits are damaged, so that the proportion of damaged fruits is considerably higher. For example, the forecast after June drop predicted a median number of fruits per tree of 89 (Q25: 84, Q75: 93) with and 84 (Q25: 76, Q75: 90) without anti-hail net. This leads to median total yields of 49.7 t/ha (Q25: 39.2 t/ha, Q75: 61.9 t/ha) with, but only 45.9 t/ha (Q25: 35.8 t/ha, Q75: 58.3 t/ha) without anti-hail netting. Without anti-hail netting, a median proportion of 64.2% (Q25: 38.4 %, Q75: 80.2 %) of the apples are damaged at harvest. The use of an anti-hail net reduced this proportion to 29.7 % (Q25: 20.4 %, Q75: 46.9 %). This is also reflected in the median high-quality yield, which was 32.1 t/ha (Q25: 21.7 t/ha, Q75: 43.1 t/ha) with and 15.6 t/ha (Q25: 8.0 t/ha, Q75: 28.6 t/ha) without anti-hail net. Due to fruit coloring problems, the probability of having no or very low high-quality yield below 0.5 t/ha (approx. One marketable apple per tree) was higher in the scenario with anti-hail net at all forecasting time points, ranging from 1.16 % in the forecast four weeks before harvest to 1.4 % in the forecast at full bloom. Without anti-hail net, the probability of a high-quality yield between 0 and 0.5 t/ha ranged from 0.1% forecasted four weeks before harvest to 0.9% forecasted before fruit thinning (Figure 5).

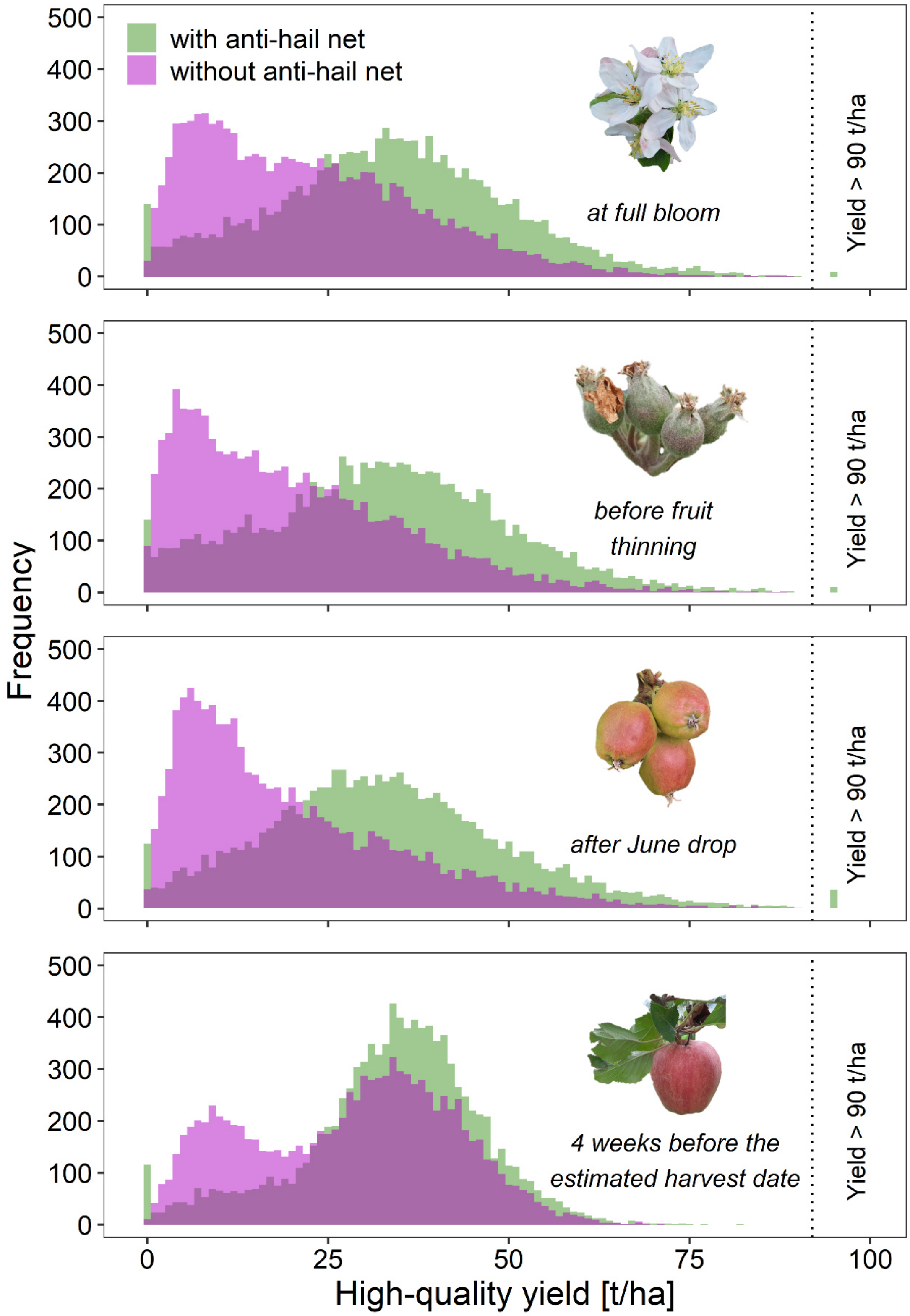


Figure 5: Frequency histograms of high-quality apple yield with and without anti-hail net predicted at four time points throughout the year: at full bloom, before fruit thinning, after June drop and four weeks before the estimated harvest date. The histograms show the results of 10,000 Monte Carlo simulation runs. Forecasted yields above 90 t/ha are shown in a combined bin on the right side of the plot.

4. Discussion

We developed ProbApple, a probabilistic model to forecast expected apple yield and high-quality yield at harvest. The model is suitable for making forecasts at four crucial moments in the production cycle: ‘at full bloom’, ‘before fruit thinning’, ‘after June drop’ and ‘four weeks before harvest’. At all time points, the model outcomes (Figure 3 and Figure 5) span wide ranges, confirming the widespread conviction among fruit growers that some degree of unpredictability is unavoidable, since quality-reducing events can occur at any time during the growing season. Nevertheless, the model provides results that go beyond farmers’ practical knowledge. ProbApple does not only show the wide range of possible yields; it also provides indications of the plausible ranges of yield and high-quality yield, as well as the probabilities of achieving certain production levels.

4.1. ‘Gala’ yield and quality predicted with ProbApple

With the input values used in our case study, the model forecasts median total yields between 49.4 t/ha (Q25: 39.6 t/ha, Q75: 60.3 t/ha) before fruit thinning and 50.4 t/ha (Q25: 44.0 t/ha, Q75: 57.8 t/ha) four weeks before harvest. These results are in line with the expectations of regional fruit-growing experts for ‘Gala’ yields of a ‘typical farm’ in the Rhineland of 50 t/ha (Muder et al., 2024). Over all model runs, predicted yields range from 0 to 163.9 t/ha. This is equal to an average total yield of 0 to 52.4 kg/tree. Such extreme values, which represent the tail ends of the outcome distribution, are rare in reality but not entirely unrealistic in ‘Gala’ apple production. Privé et al. (2011) observed yields up to 62.7 kg/tree in an experiment with ‘Gala’ on M9 rootstocks in Canada. The same experiment showed a proportion of marketable yield of 31 to 79% of the total yield (Privé et al., 2011). These results support the notion that a broad distribution of the outcome *percentage of damaged apples at harvest* is realistic and that the median values of 26.7 to 29.7% for *percentage of damaged apples at harvest* are not unrealistically high. When interpreting the results, it is important to note that the yield forecasts provide orchard-specific estimates of apple yield. These forecasts were based on year- and orchard-specific input variables (shown in Table 2). Therefore, the simulation results (Figure 3 and 5) presented here are only applicable for orchards with similar conditions (e.g. number of fruits per tree, number of trees per ha, percentage damaged at the forecasting time point) as in the case study orchard (Table 2) and should not be viewed as general probability distributions for 'Gala' apple yields across the Rhineland region. To make a prediction for an entire growing region, which could help retailers in their planning, the estimates must be based on regional rather than orchard-specific data. This means that some input distributions, and consequently the output distributions, may need to be broader to cover the variability across the entire region. Such region-wide estimates could be provided by advisors who have knowledge of production conditions throughout the region.

In our case study, the outcome distributions for total yield and high-quality yield appear quite similar across the forecasting time points ‘at full bloom’, ‘before fruit thinning’ and ‘after June drop’ (Figure 3). This similarity can largely be attributed to the assumption that manual thinning is carried out in the orchard after June drop (Table 1). Manual thinning is common practice in German apple production. Apples are removed from the trees by hand to reduce the number of fruits per tree to a target number (90 to 100 in the case study, see Supporting information 1). As far as possible, care is taken to remove mainly damaged fruits and fruits hanging too close together. This is considered in the model as *percentage of damaged fruits removed by manual thinning (tp3-tp4)*. As a result, quality-reducing events that occur before this management measure have a smaller impact on the quality yield at harvest compared to those that happen later in the season. As long as no extremely harmful event occurs before manual thinning, a broad range of factor combinations (number of fruits/flowers, risks, damage, etc.) lead to similar conditions after manual thinning.

The input variables with the highest VIP scores are variables that are part of the sub-model for yield (Figure 4). Only a few of the damage-inducing factors considered in the model reached VIP scores greater than one. This highlights that no single dominant risk is responsible for major reductions in apple quality. Instead, it is the accumulation of smaller damages over time that collectively lowers the quality yield. For fruit growers, this means they must monitor and manage a range of potential damage factors throughout the season to ensure the best possible quality.

4.2. Influence of management measures on apple quality

The importance of management measures in apple cultivation is reflected in the comparison of the quality yield with and without anti-hail net (Figure 5). Anti-hail nets provide protection from up to 100% of potential hail damage (Kiprijanovski et al., 2016). However, some damage can still occur in the border rows of an orchard, which may not be fully protected. Therefore, we included a small risk of hail damage (max. 8% as upper bound of a 90% confidence interval) in our model, also in scenarios where anti-hail netting is used (Supporting Information 1). Hail events are most frequent in the summer months June and July, although they can occur during the entire vegetation period (Puskeiler, 2013). Typically, single hail events do not affect the entire growing region. Radar-based analyses of hail events from 2005 to 2011 show that the total number of hail events during this period ranged between 6 and 8 in some areas and from 18 to 20 in others, depending on the specific location within the growing region (Puskeiler, 2013). Hail events between the forecasting time points 'at full bloom' and 'before fruit thinning' are rare. If hail does strike during this period, however, hail events may occur before fruit growers set up anti-hail nets to cover the orchard. In such cases, the possible damage (percentage of apples damaged in case of hail despite hail net (tp1-tp2)) is estimated to be nearly as high as without anti-hail nets (Supporting Information 1). Compared to production in an uncovered orchard, producing apples under anti-hail nets often leads to a lower percentage of red peel color, especially if black anti-hail nets are used. However anti-hail netting reduces the incidence of sunburn (Iglesias and Alegre, 2006). Peel coloring problems are considered in the model, leading to a higher frequency of no or low (0 to 0.5 t/ha) quality yield with anti-hail netting compared to apple production without anti-hail netting (Figure 5). Like the distributions for total and high-quality yield with anti-hail netting, the distributions of high-quality yield without anti-hail netting are similar for the forecasts at the time points 'at full bloom', 'before fruit thinning' and 'after June drop'. At the last forecasting time point 'four weeks before harvest', the unimodal distribution changes to a bimodal distribution. As in the scenario with anti-hail netting, the influence of manual thinning on high-quality yield is visible here at the first three forecasting time points during the season. The probability distribution for the percentage of visibly damaged apples shifted towards higher values for later forecasting time points but was set to be equal for scenarios with and without anti-hail netting (Table 2). For example, at the last forecasting time point 'four weeks before harvest', the percentage of visibly damaged apples was estimated at 10 to 20% (90% confidence interval). This optimistic forecast results from the assumption in our simulation that there had been no harmful hail event earlier in the season, which would have caused a difference in the degree of damage between the scenarios (Table 2). The present damage is caused by a variety of other quality-reducing factors (Figure 1). Until harvest, the share of damaged apples increases as a result of all risks that still apply during the last four weeks before harvest. The input estimations for the risk of hail damage during this time period is 14 to 48% (90% confidence interval) without anti-hail netting, but only 1 to 5% (90% confidence interval) with anti-hail netting. The simulation runs in which a hail event occurs form a large part of the left-hand frequency peak of the distribution, while the runs without hail events form the right-hand frequency peak of the bimodal frequency distribution.

4.3. Adjustment and usage of ProbApple

The model is implemented in the R programming language (R Core Team, 2024), an open source software that can be used on several operating systems. Therefore, ProbApple (Schmitz et al., 2024) can be run by interested scientists, advisors, fruit growers and other stakeholders all over the world.

Depending on the conditions under which the model is intended to be used, a variable number of input parameters should be adapted. For another orchard of 'Gala' or another season in the Rhineland, only the time point-specific inputs (Table 2) and the selection of management measures (Table 1) must be adapted (Supporting information 3). Further input values (Supporting information 1) may have to be re-parameterized to make forecasts for a different variety or a different location. The adapted values can be changed either directly in R, with a simple spreadsheet program, or even with a text editor.

To apply the model to another variety, at least the variety-dependent variables, for example bitter pit risk and damage, must be re-parameterized. The time span from full bloom to harvest and hence the length of the time periods between forecasting time points also differs between varieties. 'Gala' apples, for example, have a considerably shorter development time than apples of the 'Cripps Pink' variety (Büchele, 2018). Therefore, model users should check whether the probability distributions for the occurrence of some risk events also need to be adjusted. A user with R programming skills may also add further risks and resulting damage to the model. For all customizations, we recommend that users have a basic understanding of 90% confidence interval estimates. Estimated ranges should be so broad that the estimator is 90% sure that the actual value falls into the given range (Hubbard, 2014).

4.4. Model suitability and prospects

ProbApple is currently implemented to make forecasts for the time between full bloom and harvest. Damage during harvest and postharvest (e.g. bruise damage (Hussein et al., 2020)) is not included in the model. Furthermore, we only consider visible damage, which may be detected by the fruit growers during harvest or sorting. Internal quality parameters (Supporting Information 4) are not considered by the model. Within the bounds set by these limitations, we provide a model with a holistic perspective on the factors influencing apple quality. Although the outcome distributions for total and high-quality yield (Figure 3 and Figure 5) appear very broad at first glance, they represent reality as holistically as possible, aiming to accurately express uncertainty in the model and the system itself, as it is intended in decision analysis (Luedeling and Shepherd, 2016). Another advantage of the ProbApple model is its efficiency: once parameterized for a specific region and variety, it requires only a few estimates (Table 2) from fruit growers or apple experts to generate yield forecasts. As ProbApple runs with probability distributions for the occurrence of weather-related risks, such as hail or late spring frost, it does not require weather data observations and can be applied independently from recording weather data in the orchard. Using this model thus requires less effort than other yield prediction approaches, which require images or other complex input information (Aggelopoulou et al., 2011; Stajnko et al., 2009). Once the model is customized for a specific growing region, farm, or orchard, the key inputs required to feed the model can be estimated as part of the daily tasks in the orchard. The R software and the code for ProbApple are available as open source materials. Hence, apart from the time spent generating inputs and running the model, there are no costs for the use of ProbApple.

The forecast results that ProbApple can provide can support fruit growers in their short- and long-term planning. By deriving the most likely yield and quality yield at harvest from the outcome distributions, growers can better identify particularly high-yielding orchards, organize the harvest and plan apple storage. ProbApple provides forecasts that go beyond the assumption that orchards will consistently produce good quality yields, as many fruit growers and managers do for planning purposes. Additionally, comparing forecast results with and without specific management measures can provide valuable insights for operational decisions, such as whether to implement a particular measure in the current season. For supporting decisions on long-term investments such as hail nets, an extension of the model to a full decision support model, including financial costs and benefits would be advisable.

5. Conclusion

Through a probabilistic modeling approach based on decision analysis techniques, ProbApple enables the prediction of total and high-quality apple yield at harvest at four crucial moments in the production cycle: (i) at full bloom, (ii) before fruit thinning, (iii) after June drop and (iv) four weeks before harvest. While uncertainty and natural variability in input parameters lead to broad outcome distributions, these distributions provide an honest reflection of potential harvest outcomes in an apple orchard. Such forecasts can assist fruit growers in both short-term operational decision-making during the growing season and in long-term strategic planning. The case study results, for example, underline the importance of anti-hail netting in enhancing the production of high-quality apples. Applying the model to an orchard similar to the one in our case study requires only a few orchard-specific estimates, making ProbApple easy to implement without extensive measurement effort.

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CRediT authorship contribution statement

C. Schmitz: Writing - original draft, Software, Investigation, Visualization; L. Zimmermann: Writing - review & editing, Investigation; K. Schiffers: Writing - review & editing, Supervision; M. Balmer: Writing - review & editing, Conceptualization, Funding acquisition, Supervision; E. Luedeling: Writing - review & editing, Conceptualization, Methodology, Supervision

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Chapter 3: Evaluation of frost risk during apple bloom in Germany

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Abstract

Late spring frost events constitute a major challenge for apple producers in Germany. Extreme events like the 2017 frost can lead to dramatic yield losses, causing major economic damage for fruit growers. However, fruit-growing regions differ in terms of frost risk due to specific geographic characteristics such as continentality and elevation. For management decisions such as the choice of early- or late-blooming varieties or the application of specific protection measures, robust quantification of frost risk is indispensable. While for some regions such estimates have been generated, spatially explicit data that covers the main fruit-growing areas as well as smaller orchards, which are distributed all over the country, is still lacking.

Here, we present a nationwide analysis of the risk of late spring frost during and after apple bloom. We used phenology and temperature data from the German National Meteorological Service (Deutscher Wetterdienst) to quantify frost risk after the start of bloom (BBCH 60) (a) for a historic (1993-2007) and a recent (2008 to 2022) time period and (b) for early- and late-ripening apple varieties. We define frost as temperatures below 0°C and as temperatures below -2.2°C, with the latter being a commonly used threshold for harmful frost during apple bloom. Based on these analyses, we provide maps of spring frost risk. These maps can support the planning and management of apple orchards all over Germany.

Introduction

Apples are the most important tree fruits in Germany in terms of production area. In 2022, apples were produced in orchards covering 33,106 ha, which constitutes 67% of the country's tree fruit production area. Seventy-seven percent of all tree fruit-producing farms grow apples (destatis, 2022). Extreme spring frost events like the major freeze of 2017 can affect many of these farms, causing major economic damage (Faust & Herbold, 2017; Vitasse & Rebetez, 2018). Several studies have reported a trend towards earlier apple bloom over the last few decades (e.g. Chmielewski et al., 2004; Kunz & Blanke, 2022; Lempe et al., 2022). The effect on future frost risk has been addressed by a number of models, showing different results depending on the climate model (e.g. Hoffmann & Rath, 2013; Pfleiderer et al., 2019). All of these studies have concentrated on specific apple-growing areas rather than covering the whole country.

Fruit growing regions in Germany differ in their geographic characteristics, which leads to variation in local climate and weather. The climate in the north-west has a strongly maritime character, whereas towards the south-east, the climate grows increasingly continental (Leibniz-Institut für Länderkunde, 2003). This means that important apple-growing regions such as the Altes Land in the north and the Rhineland in the west tend to have maritime climates, while the climate at Lake Constance in the south or in Saxony in the east is rather continental. Further variation arises from elevation differences, for instance through the influence of the Alps in the south and several lower mountain ranges all over the country. Since fruit growers all over Germany require information on local frost risk in order to make informed management decisions, e.g. on the choice of early- or late-blooming varieties or on specific protection measures, we analyze historic and current phenology and temperature data to identify regional patterns and trends in the occurrence of spring frost in Germany.

Materials and methods

We used freely accessible phenology and temperature data provided by the German National Meteorological Service (Deutscher Wetterdienst (DWD), 2023c, 2023a, 2023b; DWD Climate Data Center (CDC), 2023b, 2023a) for our analysis. Apple phenology data were recorded by volunteer phenology observers, who distinguished between early and late-ripening varieties. Around two thirds of the reports for the early-ripening varieties are for the cultivar “Klarapfel” and 45 % of reports for late-ripening varieties for “Boskoop” (Deutscher Wetterdienst (DWD), 2021). From all available data, we selected a subset comprising the years 1993-2022 which contained information on the start of bloom (BBCH 60) and the time of ripening. The number of available reports decreased over time. For 1993, data for early-ripening varieties were available from 1778 locations and for late-ripening varieties from 2034 locations. Until 2022, the numbers had decreased to 742 reports for early- and 845 for late-ripening varieties. We used the daily minimum temperature at 2 m height for our frost evaluation. Such data were available for 553 weather stations in 1993 and for 472 in 2022.

We spatially interpolated the date of start of bloom between observations using regression Kriging (also known as “Kriging with external drift”). We used the mean spring temperature during the months March-May, as provided by DWD (DWD Climate Data Center (CDC), 2023c), as an explanatory covariate. Similarly, we interpolated the daily minimum temperature using elevation as explanatory factor as presented in Hudson & Wackernagel (1994). This was done for all days from the 60th until the 181st day of the year (approx. 1st of March to 30th of June). Elevation data were obtained from a digital elevation model of Germany (OpenDEM, 2011). For both tasks and each year, we fitted shape-constrained additive models (Pya & Wood, 2015). In addition to providing more flexibility than linear models, shape-constrained additive models allow stipulating a monotonous relationship between the explanatory and dependent variables, which reduces the risk of overfitting and unexpected behavior. Then, for each year, we fitted a spherical variogram model (with nugget) to the regression residuals of the additive models. Using these variogram models, we performed ordinary Kriging over a raster with a cell size of 0.05° (about 3.5*5.5 km) with a maximum of 15 Kriging points.

To validate the interpolation models, we conducted a leave-one-out cross validation for the bloom date. A sample of 100 reports per year was randomly drawn (in total 3000 samples) to run the validation. We calculated the squared error and the z-score (Equation 1) for each sample. Model accuracy was quantified using the root mean squared error (RMSE), as well as mean and standard deviation of the z-score, calculated over all samples. For the minimum temperature, we selected 100 random combinations of weather station and day of the year in the relevant period (60-181) per year (in total 3000 samples). In addition to RMSE and z-score, we calculated precision, accuracy and specificity of predicting frost occurrence (0°C and -2.2°C) with the model.

$$z - Score = \frac{Observed\ value\ at\ the\ data\ point - Predicted\ value\ at\ the\ data\ point}{\sqrt{Predicted\ variance}} \quad (1)$$

We tested two thresholds to define a frost event: i) 0°C (the freezing point of water) and ii) -2.2°C, which is known as the critical temperature for killing 10% of apple flowers and which we refer to as strong frost event. For each raster cell, we checked if temperatures below the threshold occurred between the start of bloom and the end of June. We quantified the frost risk during 1993-2007 and during 2008-2022 as the percentage of years within these periods where frost (according to the threshold) occurred after the start of bloom.

All calculations were done with the software R (R Core Team, 2021) version 4.1.2 and several contributed packages, mainly gstat (Pebesma, 2004), terra (Hijmans, 2023), stars (Pebesma & Bivand, 2023) and scam (Pya, 2023). The maps were produced with the package rasterVis (Perpi & Hijmans, 2023).

Results

Comparing the median of the start of bloom between early- and late-ripening varieties for each year separately, late-ripening apple trees started flowering 2 to 5 days later than early-ripening varieties. The earliest reported flowering onset for early-ripening varieties was the 11th of March (in 2002), whereas the latest beginning of flowering occurred on 14th of June (in 1991 and 2021). For late-ripening varieties, the earliest report for start of bloom was the 3rd of March (2005) and the latest the 15th of June (1996 and 1997). The median of the reported dates of flowering onset ranged from 12th of April (in 2014) to 5th of May (in 1996) for early- and from 16th of April (in 2014) to 9th of May in 1996 for late-ripening varieties.

Comparing the mean start of bloom between the time periods 1993-2007 and 2008-2022 for each raster cell indicates a shift towards earlier bloom in most places (Fig. 1). For early-ripening varieties, the shift in start of bloom ranged from 9.6 days earlier to 4.6 days later with an earlier start of bloom in 99.75% of the raster cells. The shift in start of bloom for late-ripening varieties lay between 8.8 days earlier and 4.7 days later, with an earlier start of bloom in 99.68% of the raster cells. The places where later bloom was recognized in the interpolated bloom data are mostly located near the country border, in the Alps or near the Black Forest Mountains. A strong shift towards earlier blossom was observed in the south-east and some regions in the west of Germany. This effect was less pronounced near the coast and in the north-east (Fig. 1).

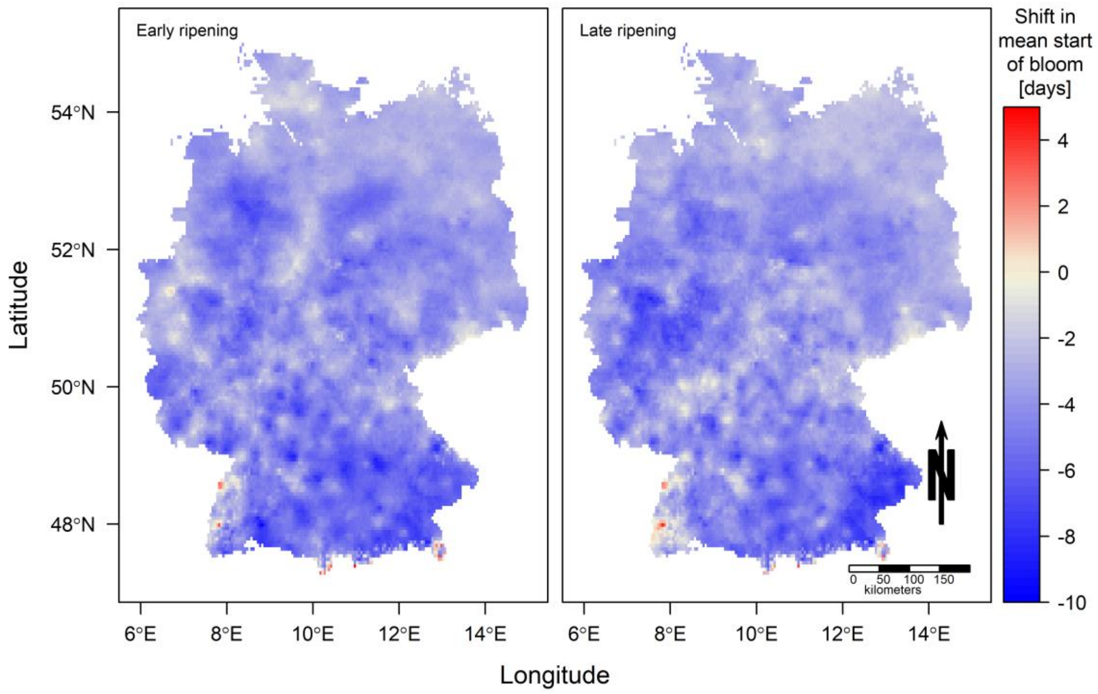

Figure 1: Shift in mean start of apple bloom between the time periods 1993-2007 and 2008-2022 in Germany for early-ripening (left) and late-ripening (right) apple varieties. Maps are based on interpolated data for the start of bloom and have a cell size of 0.05° (about 3.5x5.5 km).

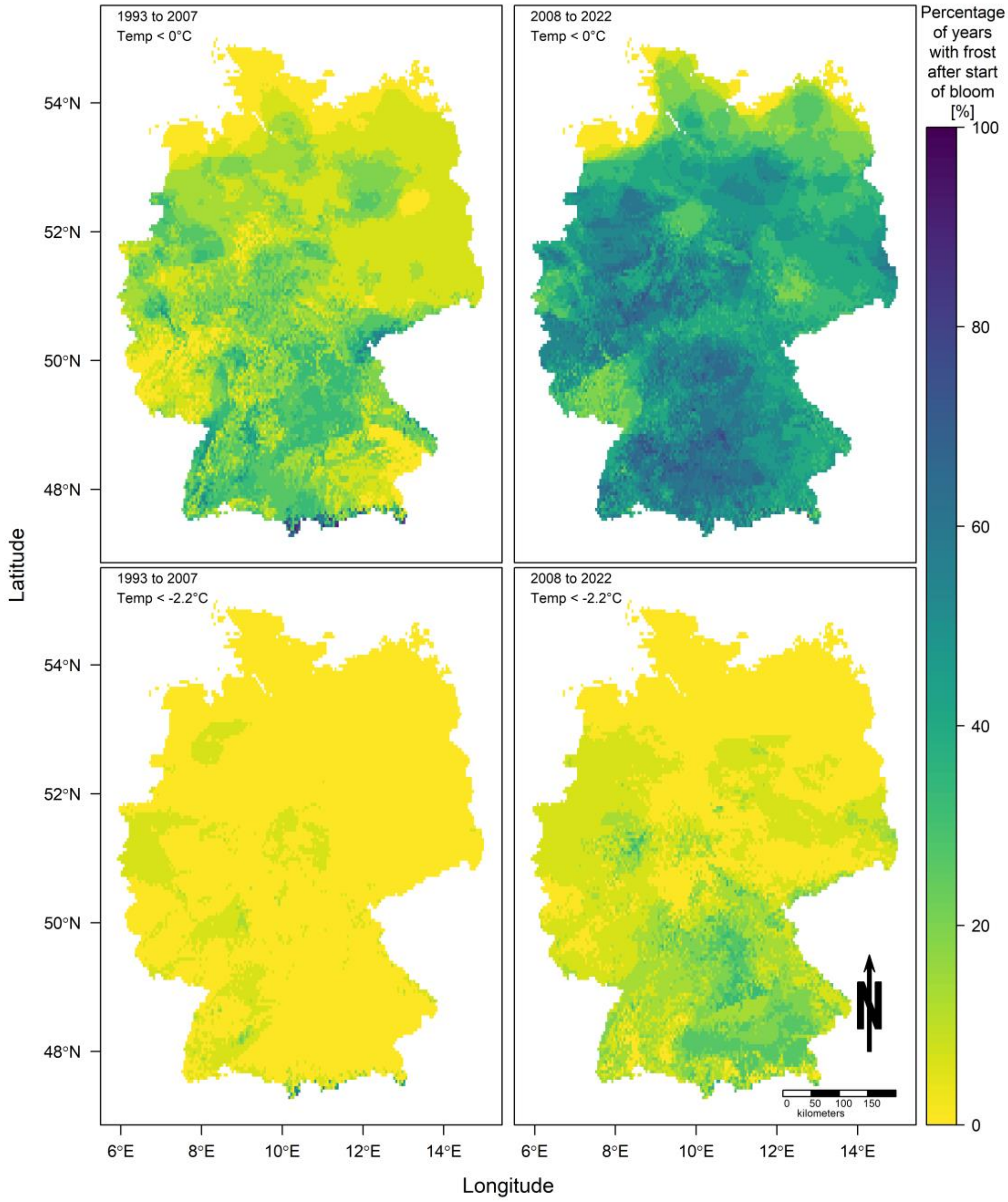

Figure 2: Percentage of years with frost, defined as temperatures below 0°C (upper row) and strong frost (< -2.2°C, bottom row) after start of apple bloom (BBCH 60) for early-ripening varieties in Germany during 1993-2007 (left) and during 2008-2022 (right). Maps are based on interpolated data for the start of bloom and daily minimum temperatures. They have a cell size of 0.05° (about 3.5x5.5 km).

For the early ripening varieties, the share of years with temperatures below 0°C ranged between 0 and 93% for 1993-2007 and between 0 and 80% for 2008-2022 (Fig. 2). In 21% of the raster cells, frost occurred in 25% or more of years (4 or more frost years within 15 years) and in 0.7% of the raster cells, frost occurred in more than half of the years between 1993 and 2007. For the 2008-2022 interval, a frost frequency of 25% or more was found for 87% of the raster cells. In 31 % of the raster cells it was 50% or higher. The frost frequency increased from the first to the second period in nearly all locations, with only a small strip along the coast (north of Germany) not hit by late frost during the second period. During a small number of spring frost events, temperatures fell below -2.2 °C. The maximum frequency of such strong frost events below -2.2°C calculated for a raster cell was 73% for 1993-2007 and 40% for 2008-2022. For 1993-2007, we found strong frost events with frequencies of ≥25% and ≥50% in 0.14% and 0.03% of the raster cells, respectively. During the second time period, the share of raster

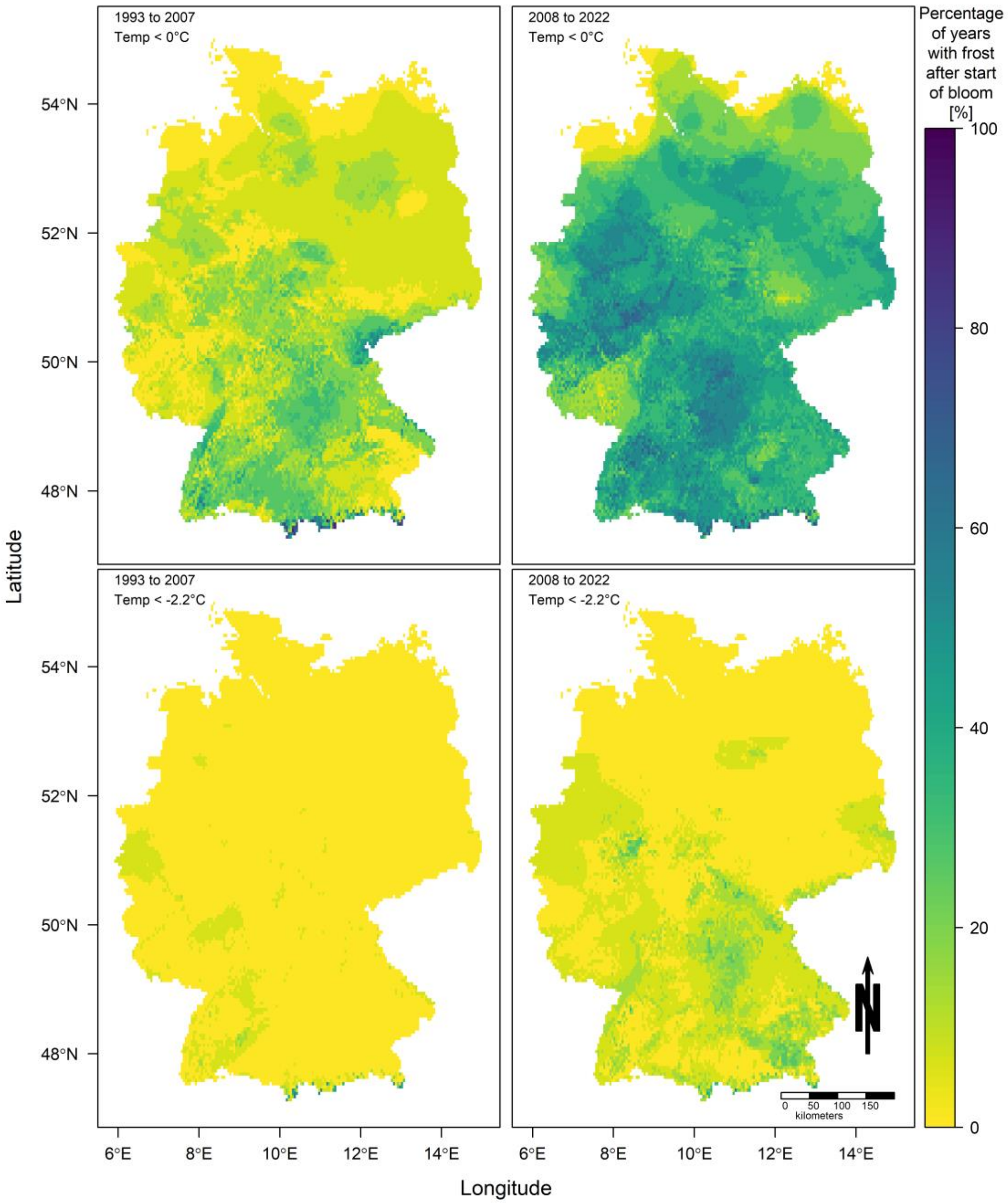

Figure 3: Percentage of years with frost, defined as temperatures below 0°C (upper row) and strong frost (-2.2°C, bottom row) after start of apple bloom (BBCH 60) for late-ripening varieties in Germany during 1993-2007 (left) and during 2008-2022 (right). Maps are based on interpolated data for the start of bloom and daily minimum temperatures. They have a cell size of 0.05° (about 3.5*5.5 km).

cells with at least 4 years with strong frosts increased to 6%, but no cells reached a frost frequency of 50% or higher (Fig. 2). Most regions with a small percentage of strong frost events during 1993-2007 were located in the middle and the west of Germany as well as in the Alps. During the later period, the frequency of strong frosts was higher, particularly in Bavaria (south west of Germany) and the Sauerland region (middle of Germany) (Fig. 2).

For the late-ripening varieties, we found similar results, with slightly lower frost frequency in many regions than for early-ripening cultivars (Fig. 3). The maximum frequency of frost events below 0°C predicted by our interpolation model was 93% for the period 1993-2007 and 87% for the period 2008-2022. A frost frequency of 25% or higher was found for 11% of the raster cells for the first period and for 81% of the cells for the second period. Spring frost occurred at 0.5% of the locations in half or more of the years between 1993 and 2007, increasing to 11% between 2008 and 2022 (Fig. 3). Comparing the maps for strong frosts shows a clear difference between early and late varieties, with lower strong-frost frequency for late-ripening varieties (Fig. 2 and 3). The effect of variety on the frost risk is less pronounced in locations with a high frost frequency. The maximum percentage of years with frost below -2.2°C was similar between early- and late-ripening varieties, at 73% during the first and 40% during the second period. The proportions of raster cells with a frequency of strong frosts of ≥25% and ≥50% were also similar (Fig. 3).

Cross-validation of the interpolated bloom dates resulted in an RMSE of 5.4 days for early- and 5.8 days for late-ripening varieties. The z-score had a mean of 0.005 with a standard deviation of 0.985 for early- and -0.007 with a standard deviation of 1.007 for late-ripening varieties.

Cross-validation of interpolated temperature data resulted in an RMSE of 1.41°C for stations that were not used to inform the interpolation. The z-score had a mean of 0.009 and a standard deviation of 1.023. The interpolation model predicted frosts below 0°C with an accuracy (correct prediction of frost or no-frost situations) of 95.7%, precision (frost occurred when frost was predicted) of 87.7 % and specificity (no frost when no frost was predicted) of 97.1%. For the threshold of -2.2°C, the accuracy in predicting frost events was 97.2%, the precision 87.0% and the specificity 97.9%.

Discussion

In line with several other studies (e.g. Chmielewski et al., 2004; Kunz & Blanke, 2022), we observed a trend towards earlier apple flowering in recent decades for most locations (Fig. 1). For a few raster cells, the interpolation model shows a trend towards later flowering. Most of those points are located near the national border in the Alps or in the area between the Rhine Valley and the Black Forest Mountains in south-western Germany. Some of these trends may have arisen from our dataset being limited to weather stations and phenology reports from Germany, which may have led to spurious interpolation results in border regions. Rugged topography, in particular large elevation differences between valleys and mountains may also compromise the quality of the interpolation. Phenology data being categorized by approximate ripening time rather than by cultivar may also have introduced some error, because the array of cultivars may have differed across the years covered by the dataset. The mean spring temperature rasters we used, were also generated through interpolation, rather than being derived from measurements in every raster cell, which may have introduced further error (DWD Climate Data Center (CDC), 2023c). Given this array of possible error sources, we consider the RMSE of 5.4 to 5.8 days that we obtained acceptable.

Frosts below 0°C hit all important apple production regions in both time periods, with a considerably higher frost frequency during the second period. Strong frosts with temperatures below -2.2°C occur much less frequently and do not always damage all orchards within a given apple production area. However, the maps show frost at a height of 2 meters above ground; lower branches may be exposed to colder temperatures during radiation frost events. For some fruit growers, it may make sense to shift the production to areas with a lower frost risk. However, this is rarely easy, since land that is suitable in terms of other location factors (e.g. soil properties) must be available. Fifteen years is a relatively short period for summarizing information for distinct climatic settings. The shortness of the intervals we compared entails a possibility of random effects. Nevertheless, we consider it safe to conclude that the frost frequency increased between the time periods, indicating that spring frost is currently a problem in apple production and probably will stay relevant over the coming decades. For long-term predictions, further research should use climate and phenology models to build frost frequency maps for future time periods.

The interpolation results indicate that the frost frequency was slightly lower for late-ripening varieties than for early-ripening ones. These varieties bloom about 2 to 5 days later than the early-ripening varieties, a pattern that we expect to persist in the foreseeable future. Accordingly, a move towards late-ripening varieties may be promising as an element of a strategy to manage frost risk in apple production. However, the maps we present only consider frost events after the start of flowering, whereas apple trees are already sensitive to frost before they flower. The critical temperature at which 10% of buds are killed increases from -9.4°C for the silver tip stage to -2.2°C for the first pink state (Ballard et al., 1981). Future research may consider enhancing our understanding of apple bud sensitivity to frost, so that frost damage models can be improved and more reliable damage estimates become possible.

Conclusion

We confirmed that late frost occurs in all important apple growing regions, even though the frequency of harmful frost events differs strongly between and within production regions. Late-ripening varieties have the advantage of starting to bloom a few days later than early-flowering cultivars, which slightly reduces the risk of spring frost damage. Further research should project future frost risk and expected damage, to enhance the information base for growers making adaptation decisions in the face of climate change.

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Chapter 4: Decision support for selecting suitable frost protection methods for apricot orchards in Germany

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Abstract

Fruit growers are increasingly interested in protecting their orchards against spring frost during bloom. The current trend toward earlier phenological development increases concerns about severe frost damage. Especially for niche products, such as apricots produced in Germany, protecting against yield losses is of crucial economic importance. The lack of precise information about the characteristics of specific frost protection methods makes it difficult to select locally appropriate frost protection strategies. Growers have access to several frost protection methods. However, these differ greatly in terms of costs, effectiveness, and labor requirement. Further uncertainty is incurred through the necessarily limited information on risks associated with differing management methods, and on current and future frost risks. We developed a decision support model to advise fruit growers on investments in frost protection. The model compares three relevant frost protection measures with different modes of action: wind machines, below-canopy irrigation, and candles that heat the orchard. We used a decision analysis approach to build a holistic model of the choice between frost protection options. We began with a conceptual model that we created together with experts and key stakeholders. The model includes all important risks and fully considers all relevant uncertainties related to the costs, benefits and risks of frost protection methods. Input parameters were gathered from the literature and through expert estimates in the form of probability distributions. We implemented the model as a Monte Carlo simulation and projected probability distributions for the Net Present Value and the annual cash flow for the different decision options. Based on this model, we evaluate the adoption of frost protection measures in apricot orchards in the federal state of Rhineland-Palatinate in southwestern Germany and provide advice to local fruit growers.

Introduction

At present, apricots are a niche product in Germany, with a production area of only around 300 ha (DESTATIS, 2022), but increasing temperatures may make this crop attractive in the future. Among the commercially produced stone fruits in Germany, apricots are the first to bloom. In Rhineland-Palatinate, flowering often starts in March (Chmielewski et al., 2009). During the years 1961-2005, the start of apricot bloom across the Rhineland area has moved forward by 17.8 days (Chmielewski et al., 2009), leading to an increased frost risk for stone fruits (Ma et al., 2019). Extreme events such as a major frost in April 2017 hit fruit growers severely (Vitasse and Rebetez, 2018). Hence, concerns about severe spring frost damage in apricots have increased, and fruit growers have become more interested in taking measures to protect their orchards against frost events during bloom.

Frost damage is caused by the formation of ice crystals within the bud, which harm plant cells (Rodrigo, 2000). To protect their fruit trees against this damage, fruit growers can choose between various active and passive measures. The available protection measures differ greatly in terms of costs, effectiveness and labor requirement (Beya -Marshall et al., 2019;

Lakatos and Brotodjojo, 2022). Furthermore, current and future spring frost risk has a high temporal and regional variability (Chmielewski et al., 2018). The lack of precise information about the characteristics of specific frost protection methods makes it difficult to select locally appropriate frost protection strategies (Luedeling and Garming, 2019).

We set out to support decision-making under high uncertainty and limited information on the comparable costs, benefits and risks that may be incurred by choosing particular frost management methods. Through the use of an innovative and customized decision-analysis approach, we want to provide advice to local fruit growers. Working with local experts, including fruit growers, we built a holistic model to evaluate the economic efficiency of active frost protection strategies for apricot orchards in the federal state of Rhineland-Palatinate in south-western Germany.

Materials and methods

We organized a participatory online workshop with 20 frost protection experts (including 4 scientists, 4 fruit growers, 7 fruit growing advisors, 3 applied scientists, and 2 sales representatives) in March 2022. The experts defined a relevant decision question for fruit growers in Germany: “In which frost protection measure should I (as a farm manager) invest, and would an investment be worthwhile?”. We used a group knowledge elicitation technique adapted from Whitney et al. (2018) to collect relevant costs, benefits and risks of frost protection measures. After the workshop, the results were sorted, summarized and used to develop a conceptual model of the effect of management investment choices on the economic output of the fruit orchards, quantified as the net present value (NPV). Based on the workshop results and the conceptual model, we implemented a simulation model. This model is a mathematical representation of the conceptual model, calculating costs, benefits and expected apricot yields of three protection measures, considering all important risks related to frost protection.

For the parameterization of the model, we made use of both literature information and expert estimates. As these estimates are typically uncertain, probability distributions of the parameter values rather than fixed values were used as model input. This enabled us to propagate the uncertainty of the input values to the model output based on Monte Carlo simulations, i.e., simulations where parameter values are randomly drawn from the input distributions.

To achieve a meaningful set of probability distributions to feed into our model we subjected a sub-group of five frost protection experts to a process known as calibration training. During the training, we taught the experts about cognitive biases like overconfidence (Kruger and Dunning, 1999) and about other biases such as the tendency for anchoring on predefined numbers (Kahneman, 2011). Through this training our experts learned about a set of techniques to improve their estimates e.g., by pretending to bet money. The techniques were practiced in the form of quizzes and games following those described by Hubbard (2014). We then asked the calibrated experts for ranges representing their 90% confidence intervals for the input variables.

We parameterized the model for the theoretical scenario of an established (5-year-old) apricot orchard in Rhineland-Palatinate, Germany on 3 ha of land with an existing drip-irrigation system and an average annual yield of 15,000 to 20,000 kg ha-1 per year-1 (90% confidence interval) in years without frost. The risk of frost during apricot blossom was estimated at 60-80% (90% confidence interval) for this region. We simulated apricot production for a time span of 10 years considering four decision options in the model:

- no protection, a baseline scenario where no frost protection was applied. This scenario had no costs but maximum risk of yield loss in the case of frost;
- candles, an option where paraffin candles are used to heat the orchard. This scenario is characterized by a high workload and high uncertainty regarding the efficiency;
- below-canopy irrigation, an option where water is sprayed on the grass and herbs around the trees. The mechanism is based on the release of sensible heat during the freezing of water. This scenario is characterized by high water demand, high investment costs and comparatively low protection efficiency;
- mobile or stationary wind machines, an option where the inversion effect is used to mix warmer air from above with colder air near the surface. These scenarios are characterized by high investment, low workload and the risk of increasing the damage when used under the wrong conditions.

Based on the probability distributions of the input parameters, we ran 10,000 Monte Carlo simulations for each option. Accordingly, for each option and year, the model simulated if a frost event occurred and calculated 10,000 values for costs, benefits, and apricot yield. We projected probability distributions for the Net Present Value (NPV) and the annual cash flow for a time span of 10 years. We conducted a Partial Least Squares (PLS) regression analysis to compute the Variable Importance in the Projection (VIP) statistic to determine input variables that substantially affect the NPV. We implemented the simulation model in the programming language R (R Development Core Team, 2022). All analyses were conducted with the R-package *decisionSupport* (Luedeling et al., 2022).

Results

The experts highlighted the benefits of frost protection measures. According to their assessment, the main benefit is the protection of flowers and young fruits, which reduces yield losses. Among the costs, experts mentioned initial costs, maintenance costs, running costs, wages, and other operating costs as relevant for frost protection measures. Initial costs include machines, materials, planning, approval and construction costs. Maintenance costs and running costs, e.g. storage and frost monitoring, are

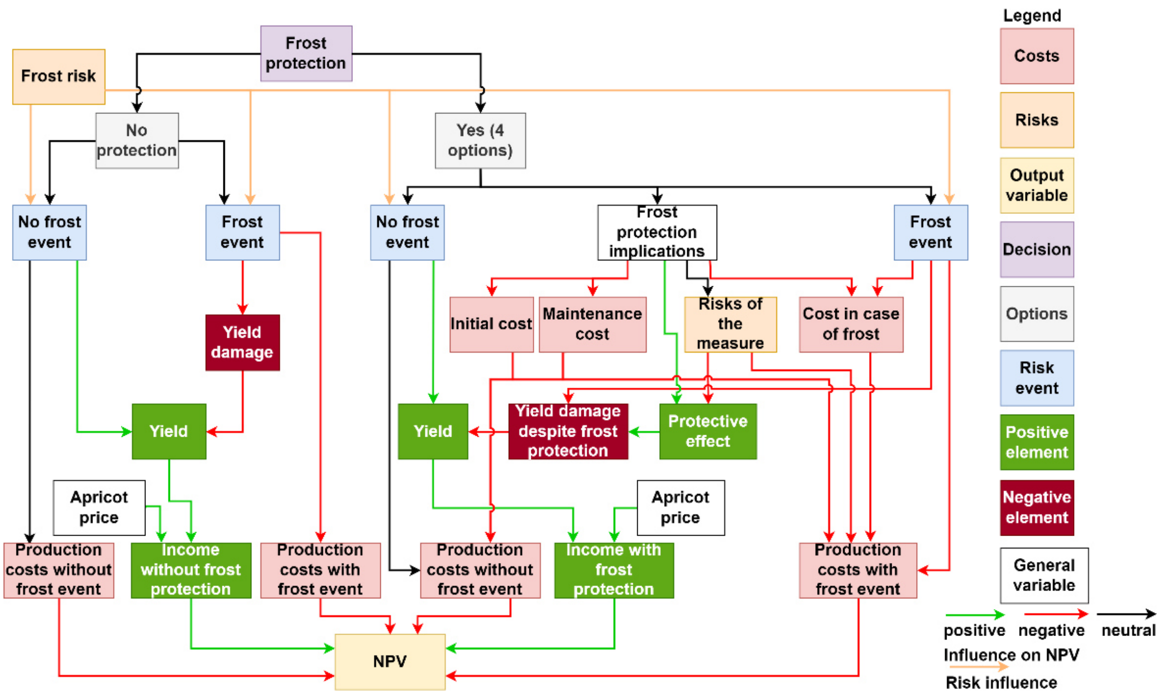

Figure 1. Summary of a conceptual cost-benefit model for spring frost protection measures in apricot orchards.

accrued annually, independently from frost events. Risks included possible management errors, technical issues, or availability problems leading to the non-effectiveness of the measures. Risks related to the usage of below-canopy irrigation include waterlogging and fertilizer leaching. Starting the wind machine under conditions without an inversion layer can lead to increased frost damage. Errors in handling the candles can lead to fire damage. The conceptual model (Fig. 1) summarizes the factors mentioned by the experts and how these factors influence the Net Present Values of the different decision options.

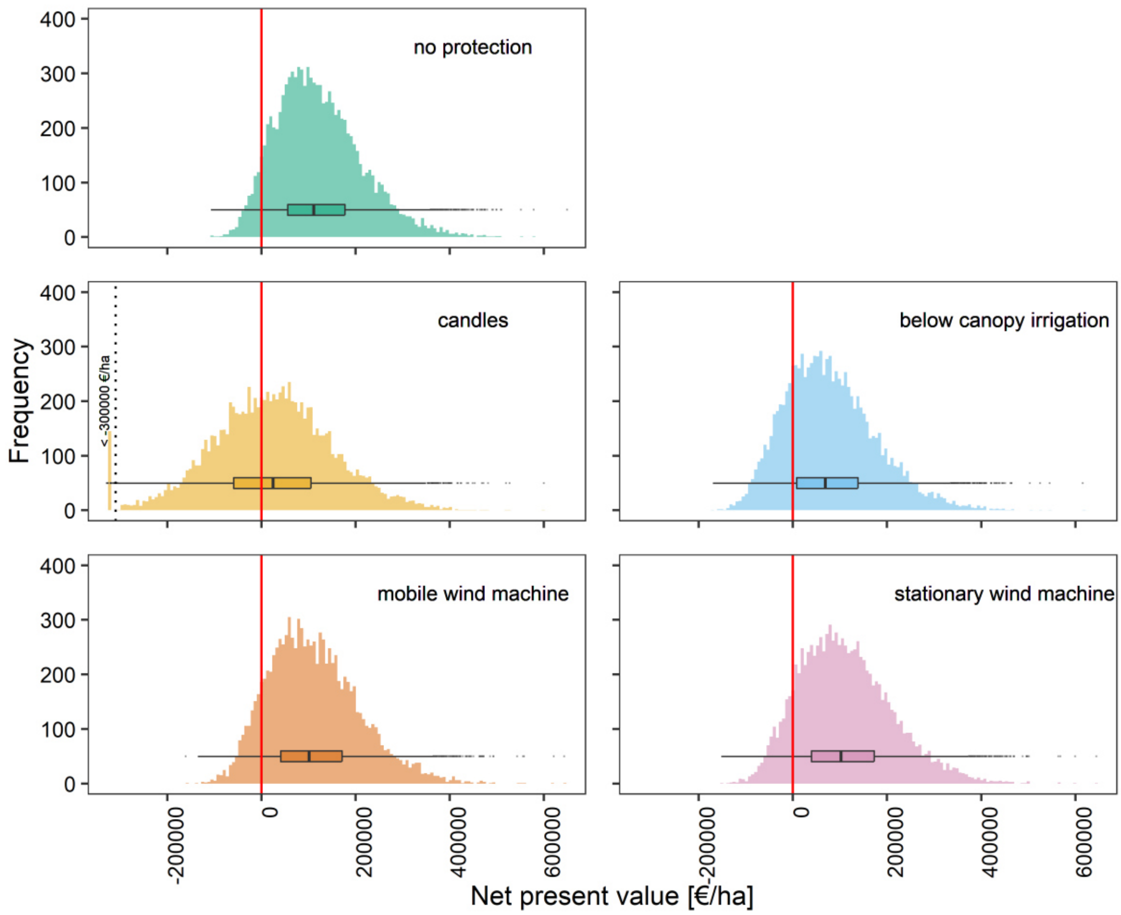

Figure 2. Frequency histograms and boxplots (from 10,000 Monte Carlo simulations) of the Net Present Value (Euros per ha) for five spring frost protection strategies in German apricot orchards over 10 years. Values lower than -300,000 €/ha are collected in the left bar, delimited by a dotted vertical line. The vertical red line indicates a Net Present Value of 0.

The projected NPV after a period of ten years differed between the frost management options (Fig. 2). None of the management options outperformed the alternative of no frost protection. Without frost protection, 90% of the outcome ranged from a loss of 7,869 €/ha to a gain of 287,363€/ha, with a 93.5% chance of obtaining positive outcomes. The highest chance of 27.2% of an economic advantage compared to no protection was found for the frost protection with stationary wind machines. With an investment in stationary wind machines, 90% of the simulated NPV values lay between -32,752 €/ha and 289,329 €/ha, with a probability of 88.3% of reaching positive outcomes. Mobile wind machines achieved similar results with an 88.6% chance of obtaining positive outcomes and an economic advantage in 25.5% of the cases. Ninety percent of the simulated NPV values lay between 28,325 €/ha 285,120 €/ha.

The lowest chance of an economic advantage was projected for below-canopy irrigation. Only in 1.7 % of the cases below-canopy irrigation outperformed the option without frost protection. With below-canopy irrigation, 90% of the outcome ranged from a loss of approximately -61,6123 €/ha to a gain of 252,175 €/ha, with a 78% chance of obtaining positive outcomes. The highest chance of 43% of obtaining negative outcomes was detected for a protection with candles. Ninety percent of the outcome for the use of candles lay between -1,878,167 €/ha and 233,256 €/ha. The chance of outperforming the 'no protection' scenario was 3.0% with candles.

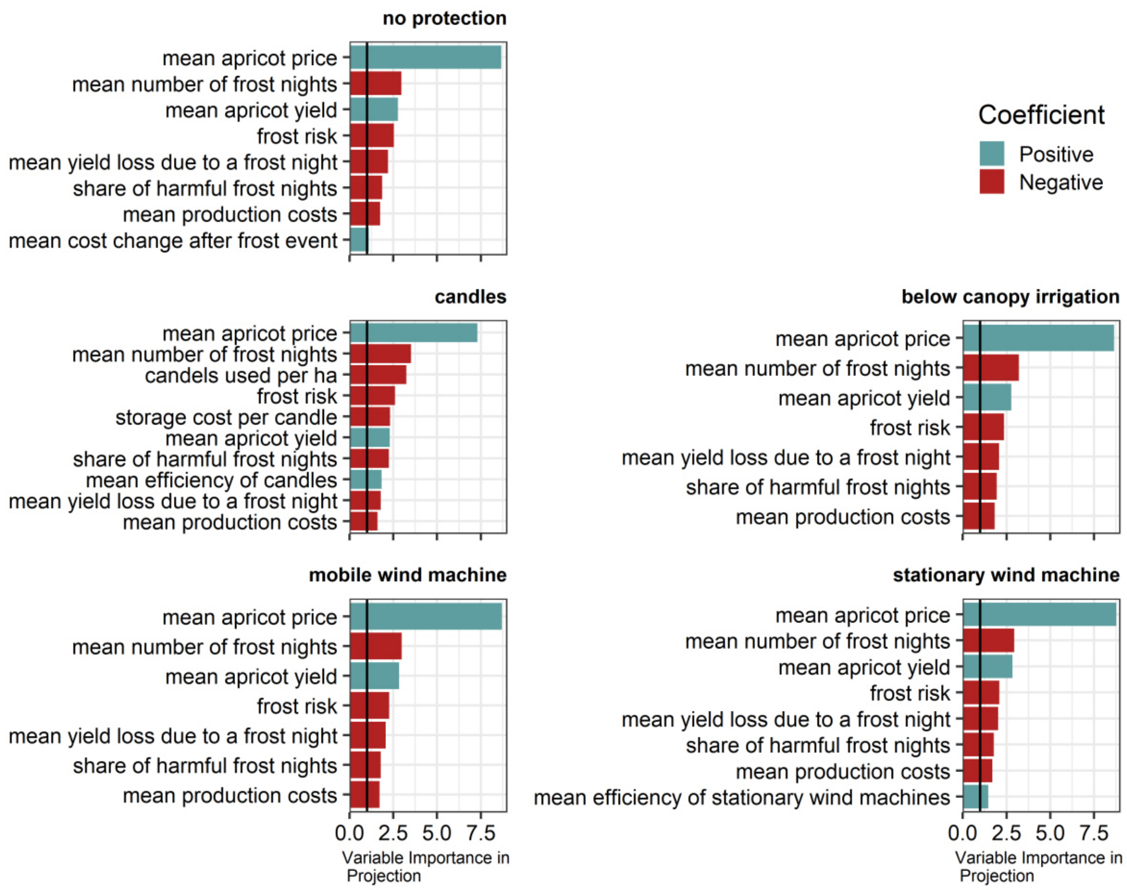

Figure 3. Variable Importance in the Projection scores of a Partial Least Squares regression model for five management strategies to manage spring frost in apricot orchards. Vertical black lines indicate the VIP=1 variable importance threshold. Red bars indicate a negative correlation with the NPV and blue bars indicate a positive correlation.

The VIP analysis revealed that the most important variable in the projection of the NPV of all spring frost management strategies was the price that a farmer gets for apricots. The apricot price has a 2 to 3 times higher VIP score as the other input variables (Fig. 3). Price and mean yield are positively correlated with the NPV. The effectiveness of the measure is important in the economic evaluation of candles and stationary wind machines. Without frost protection, the mean cost change after a frost event, which mainly describes a reduction in harvesting costs, turned out to be important and positively correlated with the NPV. Several parameters describing the frost event, including number of frost nights during blossom (in years with frost), frost risk, mean yield loss due to frost, the share of harmful frosts, are negatively correlated to the NPV for all management options.

The cash flow (Fig. 4) shows the annual results of growing apricots with different spring frost management strategies. The first year is dominated by the initial investment costs, which range from 999 €/ha to 59,222 €/ha for candles and from 26,392 €/ha to 79,257 €/ha for below-canopy irrigation. The initial cost of stationary wind machines to protect 3 ha amount to 79,176 € to 237,772 €, corresponding to costs of 17,874 €/ha to 55,486 €/ha. Mobile wind machines to protect 3 ha of apricots cost between 13,620 € and 694,924 €, corresponding to costs of 4,540 €/ha to 231,641 €/ha. In the following 9 years, the annual costs are generally exceeded by the incomes resulting in overall positive revenues: no frost protection results in net benefits in 61% of the simulated years (considering 10,000 simulation runs and years 2 to 10), the usage of stationary wind machines in 69%, mobile wind machines in 66%, below-canopy irrigation in 63% and candles in 54% of the simulated years.

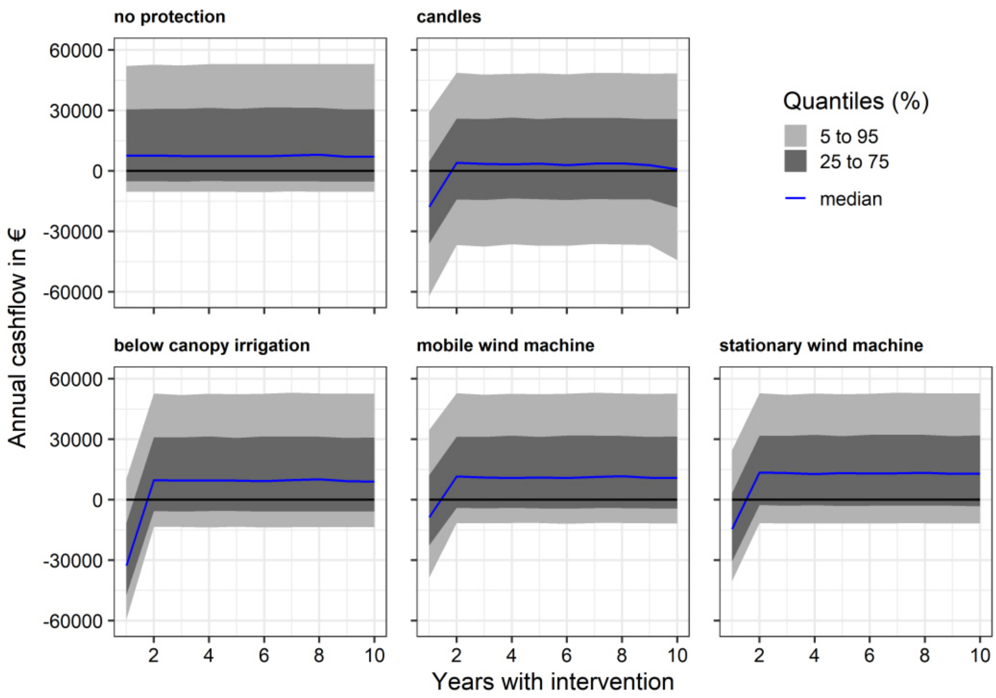

Figure 4. Probability distribution of projected annual cash flow (Euros per ha) over 10 years for five management strategies to handle spring frost in apricot orchards.

Table 1: Summary of predicted yields for five management strategies to manage spring frost in apricot orchards, from 10,000 runs of a Monte Carlo simulation.

		no protection	**candles**	**below-canopy irrigation**	**mobile wind machine**	**stationary wind machine**
Cumulative yield (over 10 years)	**Min [kg/ha]**	4504	8990	12642	10931	12078
	Max [kg/ha]	201422	206899	202816	211081	205168
	Median [kg/ha]	86728	99654	94421	95691	101024
Annual yield	**Min [kg/ha]**	0	0	0	0	0
	Max [kg/ha]	29538	68205	29538	30776	34531
	Median [kg/ha]	6309	9751	8445	8871	10238
	Percentage of years with yield <2500 kg/ha [%][a]	34.9	23.3	26.9	26.3	21.6

[a] less than ⅙ of the lower bound for the input variable “mean_yield” (mean yearly apricot yield [kg/ha])

Simulated ten-year apricot yields ranged from a minimum of 4,504 kg/ha without protection to a maximum of 211,081 kg/ha with frost protection by mobile wind machines. The median values of accumulated yield lay between 86,728 kg/ha without protection and 101,024 kg/ha with stationary wind machines (Tab. 1). Protecting the orchard with candles leads to higher yields in 99.4% of the model runs. The chance of yield increase is 98.9% with below-canopy irrigation, 98.8% with stationary wind machines, and 94.3% with mobile wind machines. The chance of yields under 2,500 kg/ha in a single year is reduced from 34.9% without protection to 26.9% with below-canopy irrigation and 21.6% with stationary wind machines (Tab. 1).

Discussion

We demonstrated the application of Decision Analysis for an investment decision in fruit growing. With this approach we could consider uncertainties and several risk factors, such as frost risk or risk of technical failure, in the calculation. This allows us to make a more holistic NPV calculation than previous decision support tools like Frost.Econ by Snyder & Melo-Abreu (2005b), which includes only a risk analysis for the frost risk.

According to our model results, producing apricots without the use of any frost protection measures was economically the best option in all the modeled scenarios. However, without frost protection, median annual yields were between 25% and 38% lower than for the below-canopy irrigation and stationary wind machines, respectively.

The economic evaluation is not the only criterion that fruit growers consider in their decision on spring frost protection. Experts mentioned reducing stress, quality assurance, delivery reliability and customer relationships, the control of vegetative growth and alternate bearing but also ensuring that the seasonal workers have enough work at harvest as reasons for investment. For these reasons, investments in frost protection could be reasonable for fruit growers and help them to meet their management needs, although the overall income might be lower.

Compared to no protection, stationary wind machines increase median annual yields by 62% and mobile wind machines by 41%. Stationary wind machines have high towers of around 10 m. They can protect a larger area and have higher efficiency than mobile wind machines (Beyá-Marshall et al., 2019). The investment costs for stationary wind machines are higher (median 84,084 €) than for mobile wind machines (median 51,133 €) (Fig. 4). When deciding on an investment, it should be noted that wind machines are noisy and their efficiency depends on the inversion strength (Gambino et al., 2007; Ribeiro et al., 2006). In Germany, a building permit is required for stationary wind machines. Some fruit growers install stationary wind turbines on mobile frames to avoid this (Baab et al., 2016). Therefore, when considering investment decisions for wind machines in fruit production, multiple factors such as cost, efficiency, and local regulations should be taken into account.

Below-canopy irrigation leads to a median yearly yield increase by 34% compared to no protection (Tab. 1). Among the modeled protection measures, below-canopy irrigation has the highest investment costs (median 42,043 €/ha) (Fig. 4). However, parts of the infrastructure, such as wells and irrigation ponds, contribute to a reliable supply of water for drip irrigation. A continuous water supply during sprinkler use is crucial for a successful below-canopy irrigation (Snyder & Melo-Abreu, 2005a). Therefore, water availability will be critical when deciding on areas suitable for below-canopy irrigation as a protection measure.

For heating the orchard with candles, the model predicted the second-highest increase in median yearly yield of 54% compared to no protection (Tab. 1). The number of candles that are used per ha is an important variable in the economic analysis (Fig. 3). The number of candles influences the workload to conduct the protection, but also the efficiency (Lakatos & Brotodjojo, 2022). Candles are criticized because of the burning of paraffin (Pauthier et al., 2022). The fire brigade and the neighborhood should be informed before use (Baab et al., 2016). Despite the increase in yield, the annual costs of apricot production with candles as frost protection can only be covered in 54% of the years. This leads to a risk of 43% of net loss over ten years. The use of candles raises concerns about economic feasibility, workload during use and environmental impact, which raises doubts about their use.

Producing apricots without any frost protection measures may be economically favorable. However, other factors such as stress reduction, quality assurance, delivery reliability, and management needs are also important considerations for fruit growers. Stationary wind machines offer higher median annual yields but also come with higher investment costs and regulatory requirements. Below-canopy irrigation can provide yield increases, making the investment worthwhile where water supply is an issue. Heating orchards with candles can increase yields but also raises concerns about economic feasibility and environmental impact. To support informed management investment decisions for frost protection measures in apricot production, further research and cost-benefit analyses are necessary.

Conclusion

Our models show that investment in frost protection measures for apricot cultivation is probably not profitable. However, it can lead to an appreciable increase in yields and reduce the risk of years with low yields. In most cases, the resulting increase in income is not sufficient to recoup the high investment costs within 10 years. The highest chance of an investment gain was found for wind machines. Overall, we show that the decision on frost protection can be of crucial economic importance. Decision analysis modeling approaches incorporate risks and uncertainty in the projection of NPV and to express the uncertainty regarding the result, which allows fruit growers to make better informed management decisions.

Acknowledgements

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Chapter 5: Model-based decision support for the choice of active spring frost protection measures in apple production

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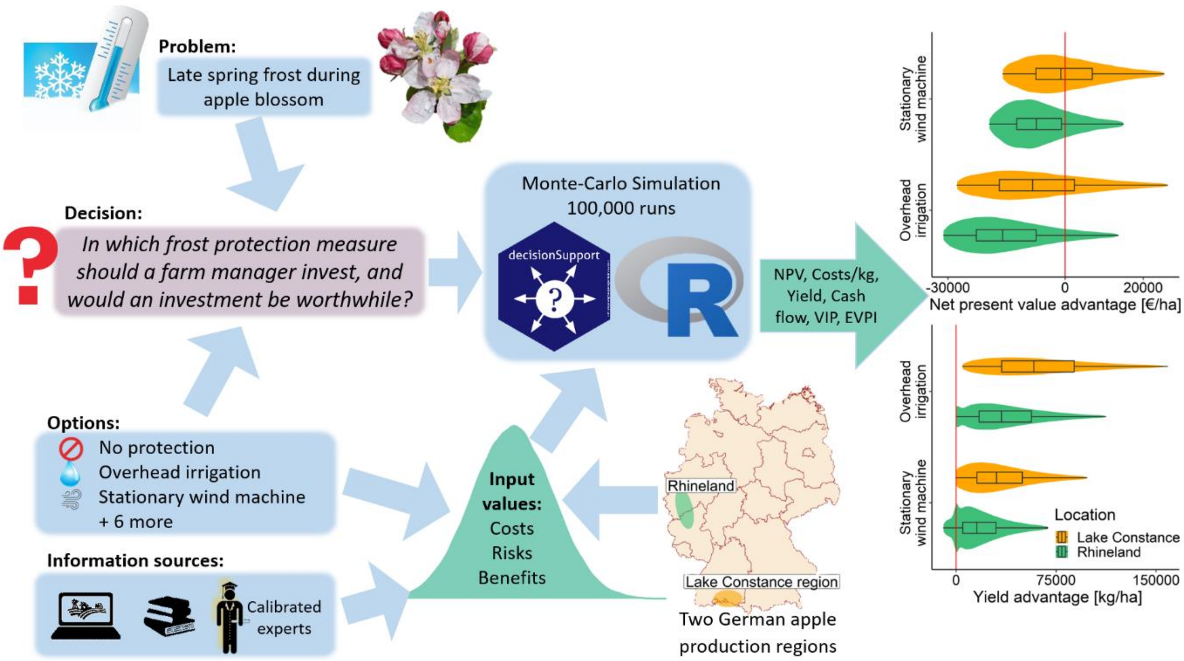
Graphical Abstract



Highlights

- Frost events cause yield losses and compromise fruit quality in apple production.
- We compared economic efficiency and yield effects of frost protection measures.
- Overhead irrigation and stationary wind machines appear most promising measures.
- Investments are more likely to be worthwhile in regions with high frost risk.
- We considered uncertainties in our holistic model for an investment decision.

Abstract

CONTEXT: Late spring frosts are a major problem for apple production in Germany. Frost events frequently lead to yield losses and quality reduction. This has motivated the development of several frost protection measures, which differ in terms of effectiveness, costs and workload. In many cases, it is an open question for fruit growers if investing in frost protection is worthwhile and which strategy would most positively affect their bottom line.

OBJECTIVE: To support decision-making, we applied a participatory process with frost protection experts to build a probabilistic model.

METHODS: The model was designed to investigate the impact of choices between eight active protection measures on an orchard's economic performance (Net Present Value, NPV) and apple yield, compared to apple production without frost protection. We applied this model to two important German apple production regions, the Rhineland and the Lake Constance region.

RESULTS AND CONCLUSIONS: The highest chance for increasing the NPV was determined for the use of stationary wind machines in the Lake Constance region (46 %), while overhead irrigation had the strongest effect on apple yield in both regions. Results indicate that frost protection measures do not necessarily increase farmers' revenues in the current economic situation. However, as these measures improve yield stability, supporting the investment in frost protection could help to maintain and stabilize regional apple production.

SIGNIFICANCE: The results indicate the importance of effectively managing uncertainties inherent in horticultural decision-making processes. They help growers make informed choices on frost protection measures to ensure economically feasible apple production under changing climatic and economic conditions.

1. Introduction

Climate change influences the phenology of fruit trees in growing regions worldwide (e.g. Chitu and Paltineanu, 2020; Kalvāne et al., 2021; Kunz and Blanke, 2022; Lee et al., 2023). In Germany, both historical observations and projections based on climate models show a trend toward earlier apple blossom (Hoffmann and Rath, 2013; Kunz and Blanke, 2022; Lempe et al., 2022; Pfleiderer et al., 2019). This trend is expected to continue in the coming decades (Hoffmann and Rath, 2013). At the same time, historical observations have identified an increasing risk of late spring frost (Kunz and Blanke, 2022). Results of current modeling approaches indicate that late spring frosts will remain frequent occurrences in the coming years (Hoffmann and Rath, 2013; Bosdijk et al., 2024).

Spring frosts occurring in the period from shortly before to after blossom cause yield losses in the frost year by directly damaging cells and affect yields of the following years by intensifying alternate bearing. Spring frost events can affect the inner and outer quality of apples at harvest (Büchele, 2018; Cebulj et al., 2021). Ice crystals, which are formed within the bud during frost, cause morphological damage, influencing the shape, appearance and size of the fruits at harvest (Rodrigo, 2000). Yield loss and quality reduction can lead to major economic damage for fruit growers (Dalhaus et al., 2020). For example, the damage caused by a major frost event in the spring of 2017 was estimated at 3.3 billion euros across Europe (Faust and Herbold, 2017). These production shortfalls increase the number of apples that Germany has to import to meet the domestic demand. While the self-sufficiency rate was 57% in the financial year 2022/2023, it dropped to just 30% in the financial year 2017/2018 after the frost event in the spring of 2017 (BMEL, 2023).

There are various active and passive measures to protect apple buds and flowers against late spring frost, which differ greatly in terms of costs, effectiveness and labor requirements (Snyder and Melo-Abreu, 2005a). Active frost protection measures can be classified according to their mode of action. Air disturbance techniques, such as employing wind machines, helicopters and selective inverted sinks, use the inversion effect and mix up warmer air from above with colder air near the ground (Hu et al., 2018; Snyder and Melo-Abreu, 2005a). The frost protection effect of sprinkler irrigation, which could be installed above or below the tree canopy, is based on the release of sensible heat during the freezing of water (Perry, 1998; Snyder and Melo-Abreu, 2005a). Different types of heaters and fuels, e.g. paraffin or wood, are available for the lighting of fires to increase the air temperature in the orchard (Snyder and Melo-Abreu, 2005a). Another heating technology are gas burners which blow hot air (between 80°C and 100°C) into the orchard to protect the buds, based on the principle of phase transition between ice, vapor and fluid water (Coman et al., 2020). This study does not consider further active protection measures like artificial fog or mulching.

The efficiency, robustness and costs differ strongly between frost protection approaches and vary with situation-specific conditions such as actual frost events, price development, and many others. Orchard managers' decisions about which protection measures to invest in under such uncertain circumstances are not trivial. We address this challenge by applying a decision analysis approach, using a methodology that has been specifically developed to support decisions under uncertainty and without perfect information on all influencing factors (Luedeling and Shepherd, 2016). The approach combines system thinking with participatory model building and the possibility of considering risk, uncertainty and variability in the model (Luedeling and Shepherd, 2016; Whitney et al., 2018). During the participatory process, experts, stakeholders and decision-makers are involved in building the conceptual structure of the model and estimating parameter values of relevant input variables (Whitney et al., 2018). The use of expert knowledge to fill knowledge gaps makes decision analysis explicitly appropriate for contexts in which data are scarce (Shepherd et al., 2015). Decision analysis is not yet widely used in agricultural contexts but has recently shown its strength in several applications, ranging from agroforestry interventions to horticultural topics (Do et al., 2020; Rojas et al., 2021; Ruett et al., 2020).

To provide an evidence base for orchard managers, we apply the decision analysis methodology to help fruit growers assess the potential value of investing in spring frost protection measures. We worked with fruit growers, advisors and scientists to build a holistic model, considering important costs, risks and benefits of eight active frost protection measures. We use Monte Carlo simulation to calculate ranges of possible outcomes for the NPV and production costs per kg apple, for two important German apple growing regions (Lake Constance in southern and Rhineland in western Germany). We compare the results to a baseline scenario of producing apples without frost protection and discuss the differences between the protection measures. Further calculations based on the model results allow us to identify important influencing variables and knowledge gaps.

2. Materials and methods

2.1. Selected apple-growing regions

We selected two important apple-growing regions in Germany, the Rhineland and the region north of Lake Constance, as case studies for our model-based evaluation. The Rhineland is located in western Germany, covering parts of the federal states of Rhineland-Palatinate and North Rhine-Westphalia. The Lake Constance region is situated in the south of Germany, north of the Alps (Fig. 1). Both regions are characterized by high geographic variability, especially in terms of elevation and distance to lakes or rivers, leading to wide ranges of annual precipitation and average annual temperatures. The average annual precipitation in the Rhineland is between 550 and 1000 mm, and the average annual temperature is between 8°C and 12°C. In the Lake Constance region, the average annual precipitation ranges from 700 to 1400 mm, with the eastern part receiving more rainfall than the west. The average annual temperature is between 6°C and 10°C (Deutscher Wetterdienst (DWD), 2023).

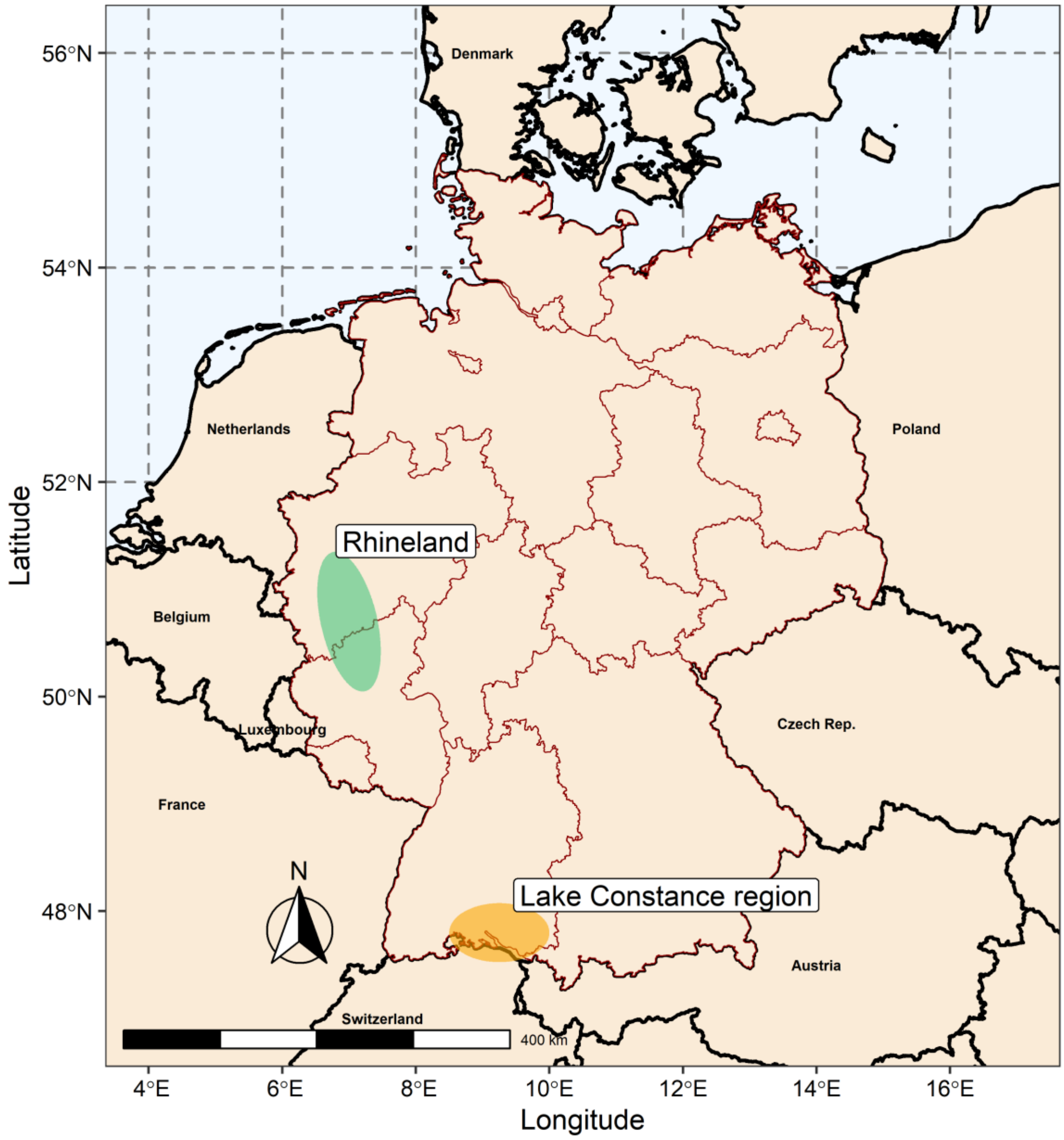


Figure 1: Map of the study regions in Germany. Black lines show the national borders and red lines show the borders of the federal states in Germany.

2.2. Participatory model building

We organized a participatory online workshop with 20 frost protection experts (including 7 scientists, 4 fruit growers, 7 fruit growing advisors and 2 sales representatives) in March of 2022. The experts agreed that the question "*In which frost protection measure should I (as a farm manager) invest, and would an investment be worthwhile?*" is relevant for fruit growers in Germany. To gather experts' knowledge about the candidate frost protection measures, we adapted a three-step group knowledge elicitation process, as described by Whitney et al. (2018), to an online format. The steps involved in the process were i) individual reflection, ii) sharing with a random partner in a breakout session, and iii) sharing and writing down ideas in moderated sessions with 3-4 experts. We used this process to elicit information on relevant costs, benefits, and risks of frost protection measures.

Based on the workshop results, we built a conceptual model to compare the economic effects of several active frost protection measures in apple production to a no-protection scenario.

Based on this model and further workshop results, we implemented a mathematical simulation model using the programming language R (version 4.1.2 (R Core Team, 2021)), with functions from the package *decisionSupport* version 1.109 (Luedeling et al., 2021). Code and simulation results are available on Zenodo (Supporting information 1 & 2) (Schmitz et al., 2024a, 2024b).

2.3. Model parametrization

2.3.1. Calibration training

We applied calibration training to enhance the experts' ability to provide unbiased estimates of model input variables. A sub-group of five frost protection experts participated in the training. During the training, we taught the experts about cognitive biases (e.g. overconfidence and anchoring) (Kahneman, 2011; Kruger and Dunning, 1999), techniques to improve their estimates using the equivalent-bet approach (Hubbard, 2014), using prospective hindsight with Klein's premortem (Klein, 2008), and avoiding narrow estimate ranges by starting with an unreasonably wide distribution. The techniques were practiced by answering trivia questions during calibration training, as described by Hubbard (2014).

2.3.2. Gathering input values

We combined the estimates from the calibrated experts, who were provided with information from all other available sources. We used all these data to arrive at probability distributions for all model input parameters in the form of 90% confidence intervals.

To get an impression of the current frost risk, we analyzed the frost occurrence during apple blossom in the years 2004 to 2023 in Klein-Altendorf (Rhineland, 50.62°N, 6.99°E and 150 m above sea level) and Bavendorf (Lake Constance, 47.77° N, 9.56°E and 481 m above sea level). We used phenology data on the beginning of flowering (BBCH 61), full flowering (BBCH 65), and the end of flowering (BBCH 69) for the apple (*Malus domestica*) varieties 'Elstar' and 'Braeburn' (KOB, 2023, 2021; Siefen, 2023). We matched these data with hourly temperature data (Agrarmeteorologie BW, 2023; Agrarmeteorologie RLP, 2023) to calculate the percentage of years with temperatures below 0°C (dry bulb temperature) three weeks before, during, and after blossom. The phenology data were collected by the DLR Rheinpfalz and the KOB (KOB, 2023, 2021; Siefen, 2023), and the weather data were provided by the agrometeorological services of the federal states and the University of Bonn (Agrarmeteorologie BW, 2023; Agrarmeteorologie RLP, 2023). We counted the number of frost nights for all years with frost occurrence and calculated the frost duration per frost night. We also evaluated the number of years with temperatures below -2.8°C in the three weeks before bloom or -2.2°C during and after bloom to assess the share of frost nights that are harmful to apple buds or flowers (Ballard et al., 1981). We used the results from analyses of past frost risk to build our range estimates on future frost risk and events in both regions. The supplementary file contains a complete overview of the input parameters and their distributions (Supporting information 1).

2.3.3. Scenarios and options

Our models simulate scenarios of newly planted four-hectare apple orchards in Germany's Rhineland and Lake Constance regions. We made several assumptions in generating these scenarios: 1. The investment in frost protection is made in the 4th year, and the orchard has a lifetime of 18 years; 2. After on-farm storage and sorting, farms in the Rhineland sell to wholesalers at 0.55 €/kg to 0.60 €/kg (90% confidence interval); 3. The farms in the Lake Constance region deliver to a producer organization directly after harvest (without on-farm sorting and storage), receiving 0.40 €/kg to 0.45 €/kg (90% confidence interval); 4. Frost protection devices have a residual value considered a gain in the 18th year. 5. There is no irrigation infrastructure on the field before planting the trees. We simulated the economic performance of apple production by considering nine decision options:

1. No protection: A baseline scenario where no frost protection is applied. This scenario is characterized by no additional protection cost and full frost damage.

The main infrastructure for irrigation systems are pumps, waterlines (to and on the field), sprinklers, and an irrigation pond. We assume that the construction of irrigation infrastructure (including the pond) is partly financed by the German agricultural investment promotion program or the support for local soil and water associations and that water is taken from the farm's own well, which gets constructed specifically for frost protection irrigation. During a frost event, a constant water flow is crucial for successful frost protection since it prevents pipes and sprinklers from freezing, which would lead to reduced protection effectiveness.

2. Overhead irrigation: Sprinklers spray water above the tree crown in this technique. Water freezes on the plant surface and forms a layer of ice around the buds. The protection effect of this technique is based on the release of sensible heat during the freezing of water. Overhead irrigation ensures high effectiveness but requires a large volume of water and continuous application (Snyder and Melo-Abreu, 2005a). In this study, we consider only sprinkler types with high flow volumes, which are commonly used in Germany. In recent years, low volume systems have been developed, but they are not widespread yet.
3. Below-canopy irrigation: Sprinklers spray water on all structures (mainly grass and herbs) below the tree crown in this technique. As for overhead irrigation, sensible heat is released during the freezing of water. Below-canopy irrigation is only suitable for light frosts but triggers fewer disease problems than overhead irrigation (Snyder and Melo-Abreu, 2005a). This option is characterized by high water demand and high variability in efficacy.

Wind machines have a rotor to mix air from above with colder air near the surface. The protective effect is based on inversion, particularly in the case of radiation frost. The protection efficacy depends on the inversion strength and technology (Beyá-Marshall et al., 2019; Ribeiro et al., 2006). Stationary wind machines can protect a larger area and have higher effectiveness than mobile wind machines (Beyá-Marshall et al., 2019). The noise emission during the use of wind machines can be a problem for fruit growers near residential areas (Gambino et al., 2007; Snyder and Melo-Abreu, 2005a).

4. Stationary wind machine: These wind machines are mounted on a concrete foundation and stay in the orchard throughout the year. We assume that a combustion engine powers the wind machine. This option is characterized by high initial investment cost, low workload, and the risk of increasing damage when misused.
5. Mobile wind machine: Mobile wind machines must be transported and mounted in the orchard before frost occurs. They are usually considerably smaller than stationary wind machines and have a lower protection efficiency (Beyá-Marshall et al., 2019). This option is characterized by a low workload and the risk of increasing damage when misused. As mobile wind machines have a lower height than stationary wind machines, they have a higher risk of being ineffective, e.g., due to very low temperatures. In this study, we consider only mobile wind machines that are less powerful than stationary ones. There are other types of mobile wind machines (on the market and self-built by converting stationary ones) that have the same protection effectiveness as stationary wind machines.

Tractor-mounted and portable gas burners blow out hot air between 80°C and 100°C. The hot air reaches every tree every few minutes (Coman et al., 2020). The frost protection effect is based on the principle of phase transition. The ice crystals on the plant's surface evaporate when the hot air reaches the tree. During the breaks, while the other trees are being blown with hot air, new ice forms and releases energy to the tree (Coman et al., 2020). Calm weather is required for successful frost protection, as slow air movement compromises effectiveness (Lakatos and Brotodjojo, 2022).

6. Tractor-mounted gas heater: The tractor-mounted or trailed version of the gas heater (known as "Frostbuster") has to be driven through the orchard during the frost event (Coman et al., 2020; Nariyanpalli et al., 2021). The main parts needed for this protection measure are the device(s) itself, tractor(s), driver(s) and a sufficient number of gas bottles. This option is characterized by low effectiveness and the risk of burning damage to leaves and buds. The tractor must be driven through the orchard during frost.

7. Portable gas heater: The portable version of gas heaters (mostly known as "Frostguard") has to be placed in the orchard during frost (Coman et al., 2020; Nariyanpalli et al., 2021). It is important to transport the portable gas heaters to the orchard before the frost event and to have enough gas bottles and the labor force to change them during use. This option is characterized by low effectiveness and the risk of burn damage to leaves and buds.

8. Candles: Candles are metal pots filled with a wick and paraffin. A few hundred candles must be placed between the trees before a frost event and lighted during the frost night. Candles have a proven effect on the temperature, but the labor requirement is high (Lakatos and Brotodjojo, 2022). The costs of buying new candles after each frost event are also high. Also, the use of paraffin candles has been criticized because of its carbon footprint and air pollution (Lakatos and Brotodjojo, 2022; Pauthier et al., 2022).

9. Pellet heaters: Pellet heaters are metal stoves that can be filled with wood pellets. They must be placed in the orchard before frost occurs and lighted during the frost night. This option is characterized by a high workload, high uncertainty about its effectiveness, and a high pellet demand.

Whether a protection measure is effective during a frost event depends not only on appropriate use but also on the weather conditions during the frost night (e.g. temperature, wind speed). To consider the differences between the measures, we expressed the probability that a particular measure is unsuitable for the present conditions with the variable *risk of ineffective protection* in our model.

2.4. Probabilistic simulation

We conducted Monte Carlo simulations with 100,000 iterations to estimate the economic performance of the nine frost protection options. A Monte Carlo simulation consists of repeated random draws from the input parameter distributions, which are then used to calculate distributions of outcomes, propagating parameter uncertainty into uncertainty about results. Based on this approach, we computed the NPV, the annual cash flow, the production costs per kg apple, and the apple yield. In our analysis, mature orchards (trees at their full bearing capacity) are defined as orchards in their 5th year or older. In contrast to the costs over the whole orchard lifetime, the production costs in mature orchards do not consider the initial investments needed to establish the orchard and the frost protection infrastructure.

We also conducted a sensitivity analysis in the form of a Partial Least Squares (PLS) regression analysis, using the Variable Importance in the Projection (VIP) statistic to evaluate the influence of each input variable on the model outcome (Luedeling and Gassner, 2012). We set a threshold of 1 to identify input variables that substantially affect the NPV.

To identify critical knowledge gaps in our model inputs, which limit the ability to make clear frost protection recommendations due to their uncertainty, we calculated the Expected Value of Perfect Information (EVPI) for each input variable. The EVPI compares the expected value of a decision made with perfect information with the expected value of a decision taken with the current level of uncertainty of the model inputs. The EVPI indicates the maximum amount of money a rational decision-maker should be willing to invest to obtain perfect information on the respective variable

(Hubbard, 2014; Lanzanova et al., 2019). We used the 1-level method described by Strong and Oakley (2013) and an implementation by Kopton (2024) to calculate the EVPI based on the Monte Carlo results.

3. Results

3.1. Conceptual model

Our model is based on the main effect of frost protection measures, which is the reduction of yield losses by protecting flowers and young fruits against frost damage. Regarding initial costs, experts listed machines, materials, planning, building permits, and construction as relevant items for frost protection measures. Running costs included maintenance costs, storage, frost monitoring, wages, and other annual operating costs. The annual production costs were influenced by frost occurrence and yield. The experts listed management errors, technical issues, or availability problems as possible risks to the effectiveness of the measures. Risks related to below-canopy or overhead irrigation include waterlogging and fertilizer leaching. Infections with *Pseudomonas syringae* bacteria or branch fractures due to heavy ice structures are further risks related to overhead irrigation. Starting the wind machine without an inversion layer can lead to increased frost damage. Incorrect handling of candles or pellet heaters can lead to fire damage. The hot air blown out by tractor-mounted and portable gas heaters may lead to burns on flowers and young leaves. The conceptual model (Fig. 2) summarizes the factors mentioned by the experts and the mechanisms through which they affect the NPV of the different decision options.

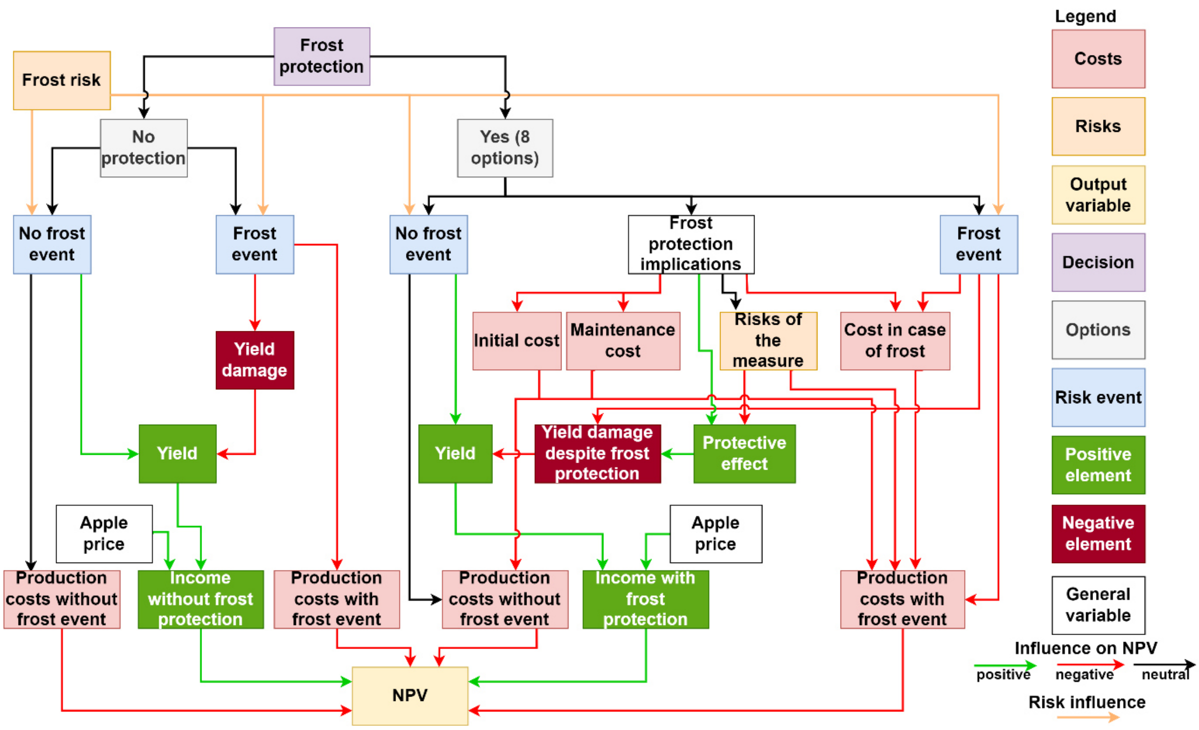


Figure 2: Summary of a conceptual cost-benefit model for spring frost protection measures in apple orchards. The model is based on all available information, including a participatory workshop and discussions with experts.

3.2. Frost events – Past years and model prediction

In the observations from Klein-Altendorf, temperatures below 0°C during bloom were detected in 7 years in Elstar and 9 years in Braeburn in the period 2004 to 2023. Frosts occurred during the three weeks before bloom in 80% and 85% of the years for Braeburn and Elstar, respectively. Frost events after bloom were observed in four years in Elstar and three years in Braeburn (Fig. 3). In frost years, the number of days with frost three weeks before, during, and after bloom reached 1 to 11 days with a median of 3. In 10% of these cases, the temperature fell below the threshold at which apple flowers are known to be considerably damaged. During frost nights, the temperature remained below 0 °C for an average of four hours.

The observations from Bavendorf showed that frost during flowering occurred in five years between 2004 and 2023. In 85% of the years, temperatures below 0°C occurred during the three weeks before bloom. Frosts after bloom occurred in two years in Elstar and one year in Braeburn. In frost years, the number of days with frost during the study period reached 1 to 13 days per year, with a median of 3 in Braeburn and 3.5 in Elstar. The share of frost events with temperatures below the critical value was 25% and 24% for Braeburn and Elstar, respectively. During frost nights, the temperature remained below 0 °C for an average of five hours.

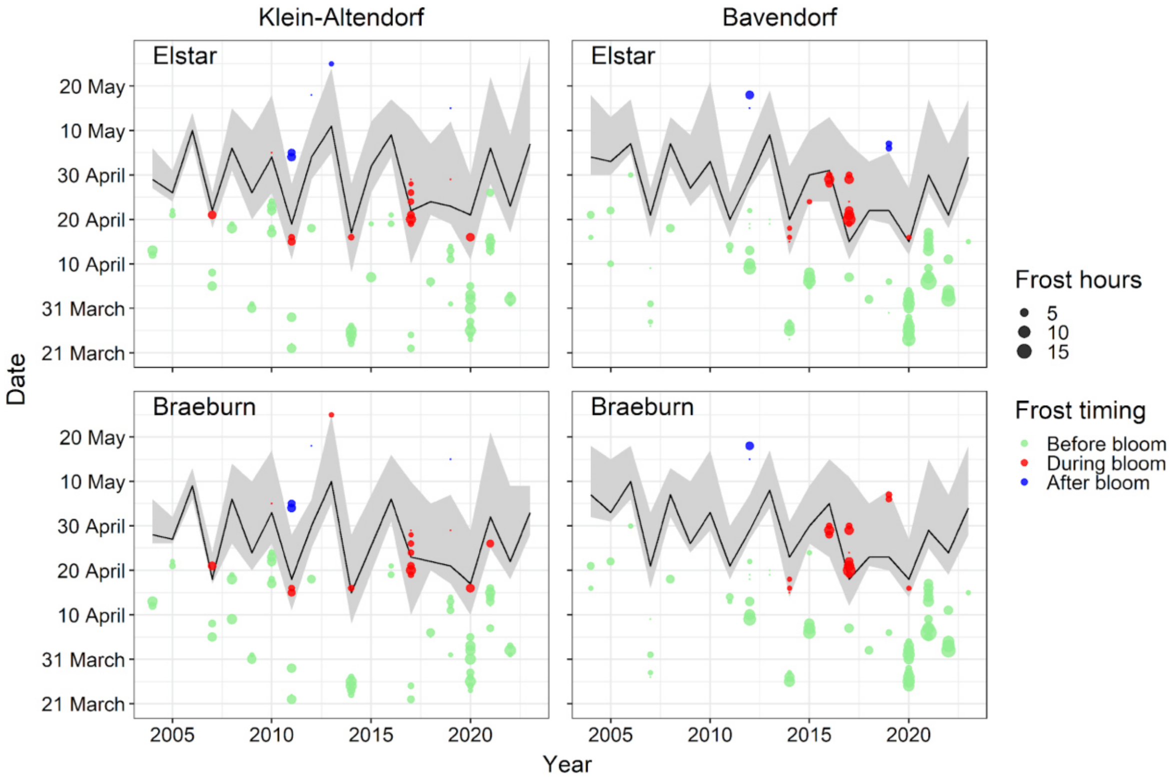


Figure 3: Spring frost events (defined as hours with a dry bulb temperature below 0°C at 2 m above the ground) three weeks before, during, and after apple bloom for two varieties at two locations during 2004-2023. The dot colour indicates frost timing, and the dot size marks the number of frost hours. The black line indicates full bloom (BBCH 65), and the grey ribbon shows the time from the beginning (BBCH 61) to the end (BBCH 69) of bloom. Klein-Altendorf is located in the Rhineland and Bavendorf near Lake Constance.

The two regions differ mainly in the share of frost events that are harmful to the trees (Tab. 1).

Using the estimated input values, the model predicted a higher number of harmful frost events for the Lake Constance region than for the Rhineland (Fig. 4). The median predicted number of years with harmful spring frost in an 18-year stretch was 4 in the Rhineland and 7 in the Lake Constance region.

3.3. Important drivers of profitability

To clarify which variables strongly influenced the profitability of the decision to invest in various frost protection measures, we interpreted the Variable Importance in the Projection (VIP) score of a Partial Least Squares (PLS) regression that statistically related variation in the projected NPV to variation in all input variables.

Table 1: Input estimates describing spring frost occurrence in the Rhineland and the Lake Constance region. The values indicate the lower and upper bounds of a 90% confidence interval. Probability distributions are used as defined in the R package *decisionSupport* (Luedeling et al., 2021).

Scenario	Variable	Distribution	Lower	Upper
Rhineland	Risk of frost during tree blossom (%)	0-1-truncated normal	45	90
	Time with a temperature below 0°C per night (h)	positive normal	2	5
	Number of frost nights during blossom in a year with frost	positive normal	2	6
	Share of frost events that are harmful to the flowers (%)	0-1-truncated normal	9	11
	Coefficient of Variation of the frost duration (%)	positive normal	40	100
	Coefficient of Variation of the number of frost nights (%)	positive normal	50	110
Lake Constance	Risk of frost during tree blossom (%)	0-1-truncated normal	30	90
	Time (in h) with a temperature below 0°C per night	positive normal	2	7
	Number of frost nights during blossom in a year with frost	positive normal	2	6
	Share of frost events that are harmful to the flowers (%)	0-1-truncated normal	24	26
	Coefficient of Variation of the frost duration (%)	positive normal	50	180
	Coefficient of Variation of the number of frost nights (%)	positive normal	50	140

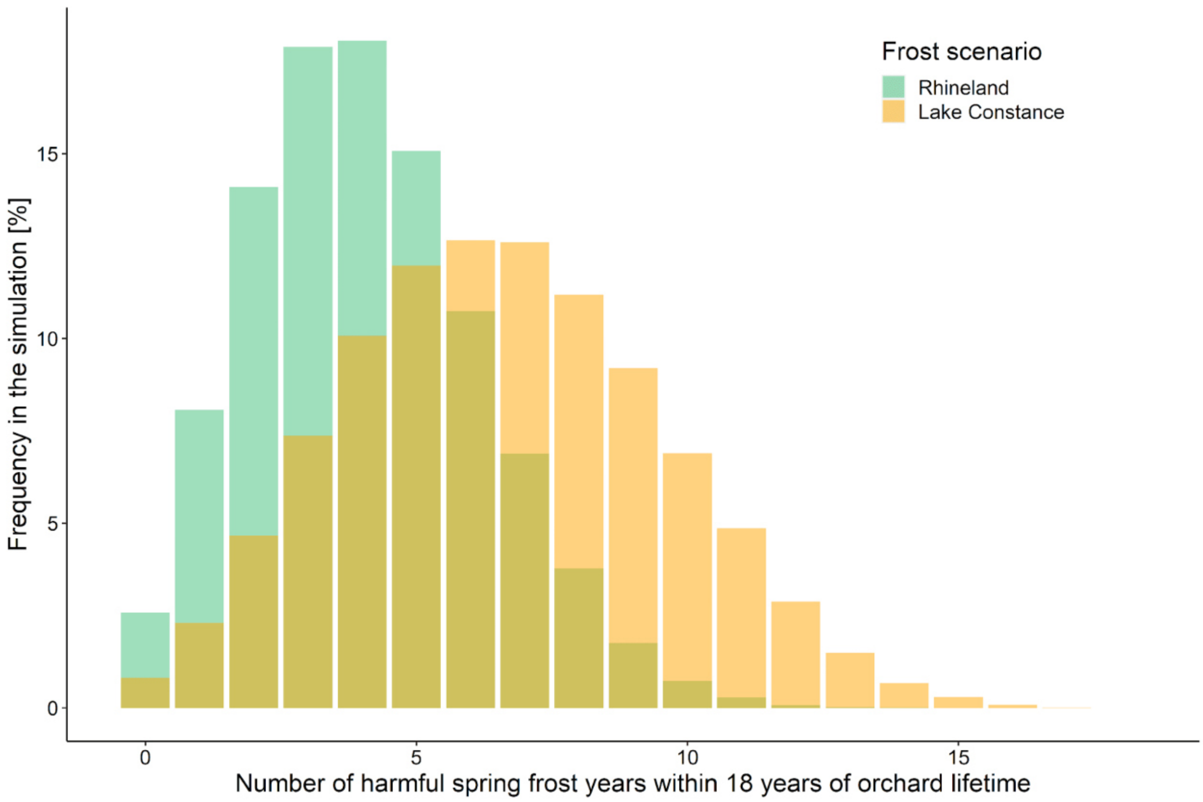


Figure 4: Histogram of the number of years with harmful spring frost events without frost protection within 18 years of orchard lifetime predicted by the decision model over 100,000 Monte Carlo runs. The green bars show the simulation results based on input estimates for the Rhineland region, and the orange bars for the Lake Constance region.

We found that variables that describe the frost or its effects, such as *frost risk* or *mean yield loss due to a frost night*, were strongly (and positively) correlated with the economic outcomes of investing in frost protection options (Fig. 5, Supporting Information 3). The protection efficiency and, for some options, the apple yield also correlate positively with the economic success of the introduction of frost protection measures. The economic outcome of an investment in frost protection was strongly (and negatively) correlated with risks that reduce the protection success, e.g. the *risk of excessively windy weather*, which makes it impossible to use overhead irrigation while maintaining the costs incurred during the acquisition, maintenance and use of frost protection measures (Fig. 5, Supporting Information 3).

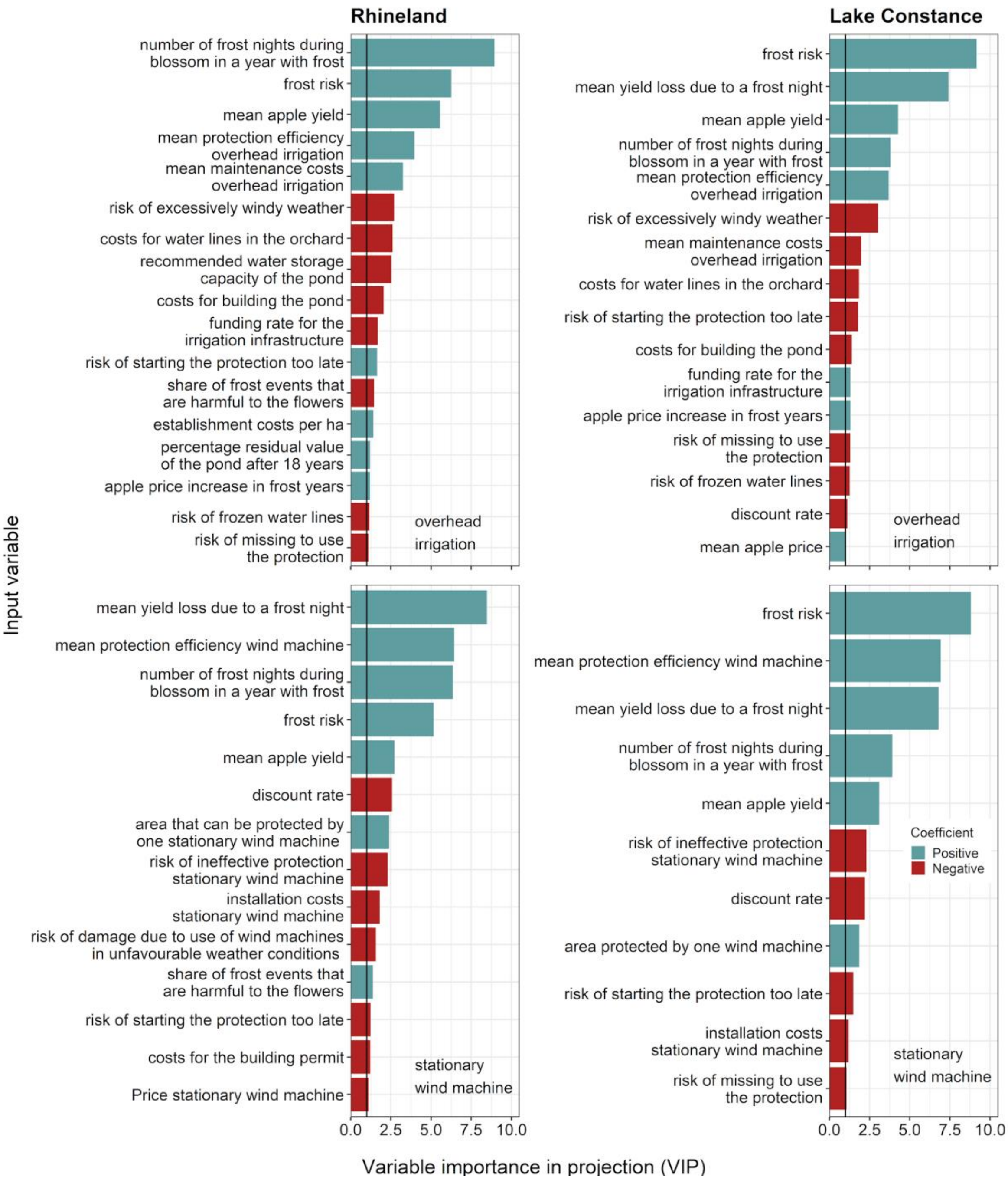


Figure 5: Variable Importance in the Projection scores of a Partial Least Squares regression model for the decision between the options overhead irrigation (upper row) or stationary wind machine (bottom row) and the 'no protection' scenario. The left column displays results for the Rhineland and the right column for the Lake Constance region. Vertical black lines indicate the VIP=1 variable importance threshold. Red bars indicate a negative correlation with the NPV of the decision and blue bars indicate a positive correlation.

3.4. Economic comparison of active frost protection measures

Based on current assumptions, apple production in both regions did not always turn out profitable. The projected median NPV without protection was -49,457 €/ha (5% Quantile (Q5): -115,494 €/ha; 95%-Quantile (Q95): 22,936 €/ha) in the Rhineland and -87,645 €/ha (Q5: -154,093 €/ha; Q95: -17,933 €/ha) in the Lake Constance region (Supporting Information 4). Comparing the NPV with and without frost protection shows that the investment in frost protection could pay off for some options (Fig. 6). The highest chance of an NPV gain compared to apple production without protection was identified for stationary wind machines. In this option, the NPV was increased in 46% of the model runs for the Lake Constance region and 25% of the model runs for the Rhineland. The second highest chance for an increase in NPV was overhead irrigation, with 32% at Lake Constance and 15% in the Rhineland. For all options, the chance of achieving a financial advantage by investing in frost protection was higher at Lake Constance than in the Rhineland (Fig. 6).

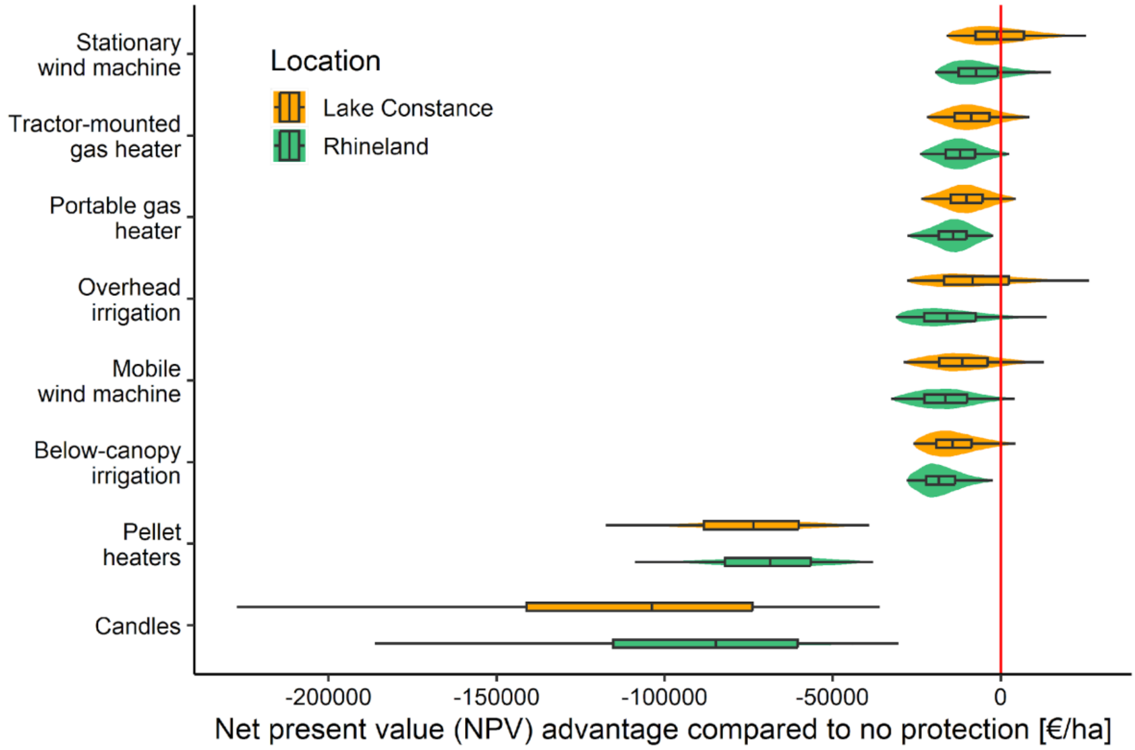


Figure 6: Difference in Net Present Value [€/ha] of several decision options of implementing frost protection measures in apple orchards compared to 'no protection' (i.e. the NPV of the decision option minus the NPV of apple production without frost protection). Box- and violin plots show the values between the 5 and 95 percent quantiles of 100,000 Monte Carlo simulation runs of the decision model. Green boxes show the results for the Rhineland and orange boxes for the Lake Constance region.

The cash flow (Fig. 7) shows the annual results of growing apples without frost protection (Fig. 7 upper row) versus income using stationary wind machines (Fig. 7. lower row) in the Rhineland and the Lake Constance region. The first year was dominated by the orchard planting and establishment costs. The first income from the orchard was generated in years two and three. In year 4, frost protection measures were implemented (Fig. 7, Supporting information 5). The average initial investment costs for frost protection measures are similar at both locations. The median initial investment had a wide range of costs. The lowest-cost option was portable gas heaters in the Rhineland at 6498 €/ha (Q5: 4348 €/ha; Q95: 12,386 €/ha). The highest investment was needed for overhead irrigation in the Lake Constance region at 26,975 €/ha (Q5: 21,399 €/ha; Q95: 34,194 €/ha) (Supporting Information 7).

In the following years, costs are incurred for farmers who maintain and use the frost protection measures. The annual apple yield increased over the first 4 years. Without frost protection, a median annual yield of 43 t/ha (Q5: 11 t/ha; Q95: 60 t/ha) in the Rhineland and 39 t/ha (Q5: 3 t/ha; Q95: 59 t/ha) in the Lake Constance region was predicted in mature orchards (Supporting Information 8). Income was mainly generated from the sale of the apples. Without frost protection, cash flows remained constant after the first two years. In the case of stationary wind machines, the residual value of the machines led to increasing annual result in the final year of the simulation (Fig. 7).

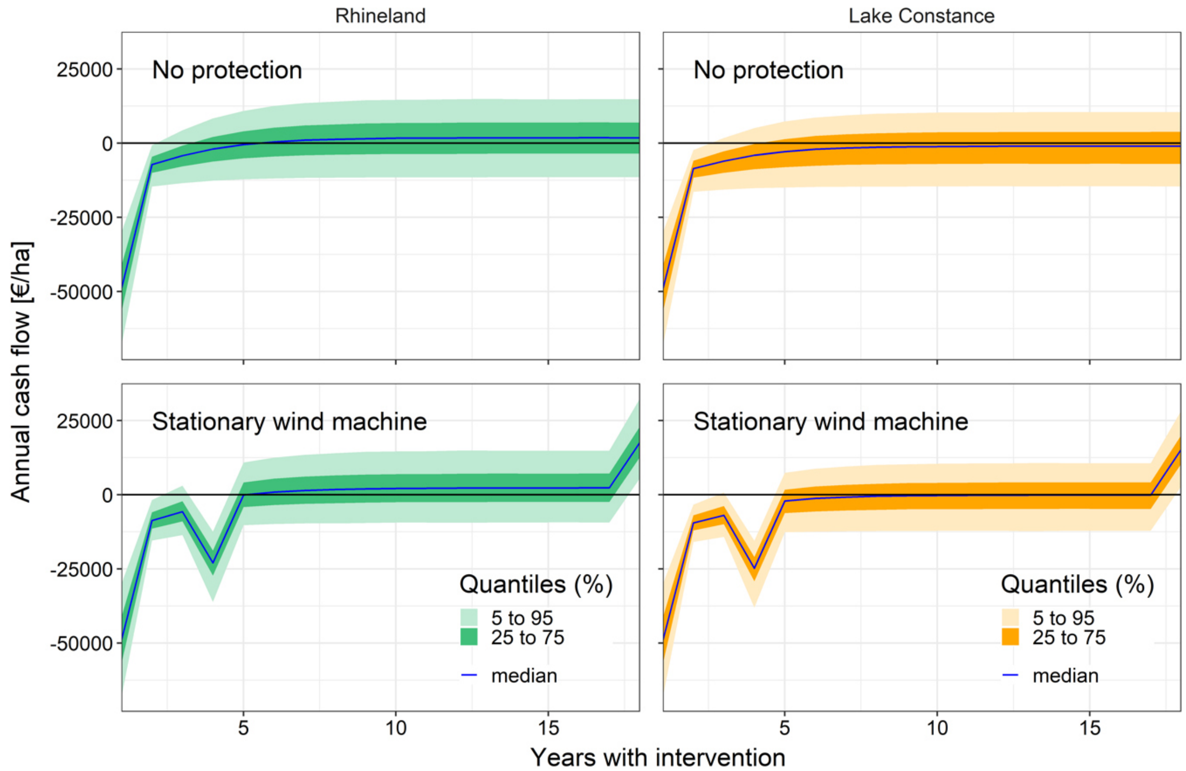


Figure 7: Probability distributions of projected annual cash flow (Euros per ha) over 18 years of apple orchard lifetime without frost protection (upper row) and protected against spring frosts with a stationary wind machine (bottom row). The left column displays the simulation results for the Rhineland and the right column for the Lake Constance region. The probability distributions were generated with 100,000 Monte Carlo simulation runs of the decision model. Supporting information includes cash flows for other options (Supporting information 7).

In our baseline model, a farmer needs 0.65 €/kg apples (Q5: 0.53 €/kg; Q95: 0.86 €/kg) in the Rhineland and 0.61 €/kg (Q5: 0.45/kg €; Q95: 0.96 €/kg) in the Lake Constance region to cover all apple production costs (Fig. 8). At Lake Constance, an investment in overhead irrigation (Q5: 0.47 €/kg; Q95: 0.86 €/kg) or stationary wind machines (Q5: 0.47 €/kg; Q95: 0.90 €/kg) did not change the median returns needed to cover all costs. Investing in other options increased the production costs per kg apple over the whole orchard lifetime (Fig. 8).

For mature orchards, a median of 0.55 €/kg (Q5: 0.45 €/kg; Q95: 0.72 €/kg) covered the yearly costs without frost protection in the Rhineland (Supporting Information 6). The use of overhead irrigation (Q5: 0.45 €/kg; Q95: 0.68 €/kg) and stationary wind machines (Q5: 0.45 €/kg; Q95: 0.69 €/kg) could reduce this to 0.54 €/kg. Producing apples with below-canopy irrigation or mobile wind machines led to similar costs as the baseline scenario. In our simulations, a fruit grower at Lake Constance needed a median return of 0.49 €/kg (Q5: 0.36 €/kg; Q95: 0.78 €/kg) to cover costs in mature orchards without frost protection. The use of overhead irrigation (Q5: 0.35 €/kg; Q95: 0.65 €/kg), stationary wind machines (Q5: 0.35 €/kg; Q95: 0.68 €/kg), mobile wind machines (Q5: 0.36 €/kg; Q95: 0.71 €/kg) or below-canopy irrigation (Q5: 0.36 €/kg; Q95: 0.72 €/kg) reduced this value to 0.45, 0.46, 0.47 and 0.48 €/kg respectively. The projected average cost per kg of apples using a tractor-mounted gas heater was similar to that without protection (Supporting information 6).

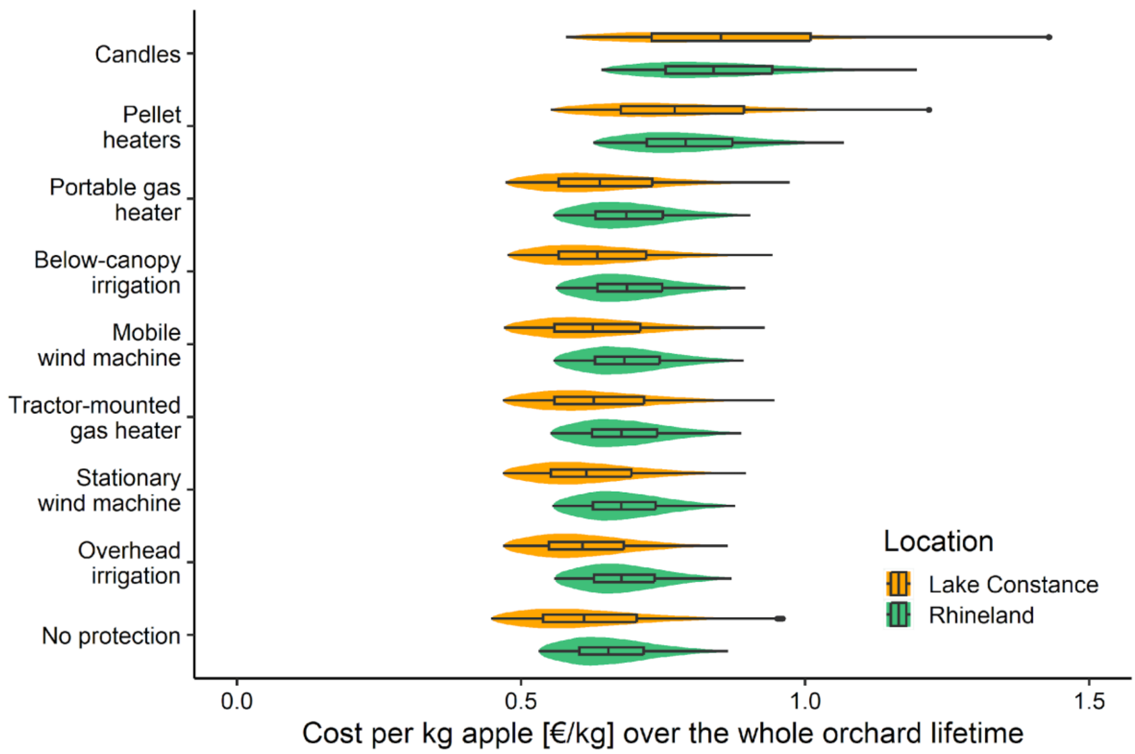


Figure 8: Total production cost per kg apple over the whole orchard lifetime of 18 years (i.e. the returns a fruit grower must receive to cover all his costs for apple production). Box- and violin plots show the values between the 5 and 95% quantiles of 100,000 Monte Carlo simulation runs of the decision model. Green boxes show the results for the Rhineland and orange boxes for the Lake Constance region.

An investment in frost protection measures can increase the accumulated yield. Overhead irrigation was characterized by the highest probability of yield increase, with a 90% chance of yield increase in the Rhineland and a 96% chance at Lake Constance. Investment in candles showed an 87% chance of yield increase in the Rhineland and 94% at Lake Constance. Tractor-mounted gas heaters (38% chance of increase) and portable gas heaters (13% chance of increase) in the Rhineland and portable gas heaters (25% chance of increase) at Lake Constance had a lower chance of increasing yield (Fig. 9).

The median accumulated yield over an orchard's lifetime could be increased by up to 12% at Lake Constance (619 t/ha, Q5: 422 t/ha; Q95: 827 t/ha) and 7% in the Rhineland (675 t/ha, Q5: 486 t/ha; Q95: 871 t/ha) by investing in overhead irrigation. Our model predicted a slight decrease in median yield when using portable gas heaters in the Rhineland (3% decrease), portable gas heaters at Lake Constance (2% decrease), or tractor-mounted gas heaters in the Rhineland (0.6% decrease).

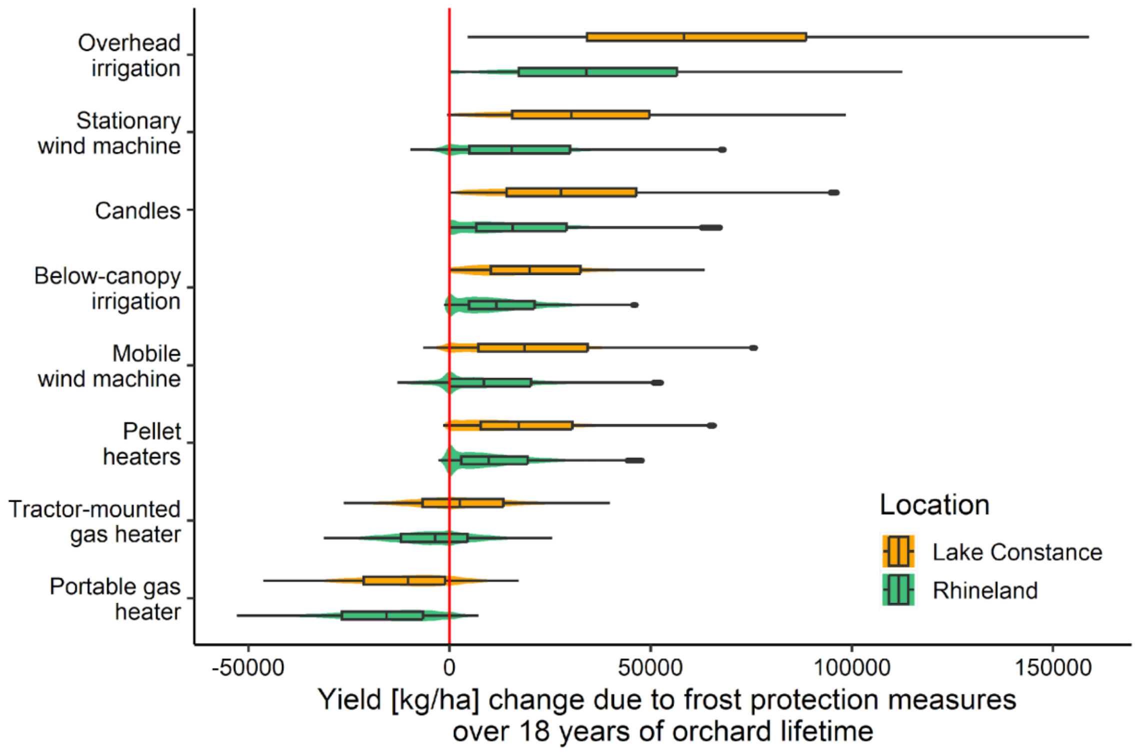


Figure 9: Difference in the accumulated apple yield [kg/ha] over 18 years of orchard lifetime for several decision options of implementing frost protection measures in apple orchards compared to 'no protection' (i.e. accumulated yield of the decision option minus accumulated yield of apple production without frost protection). Box- and violin-plots show the values between the 5 and 95% quantiles of 100,000 Monte Carlo simulation runs of the decision model. Green boxes show the results for the Rhineland and orange boxes for the Lake Constance region.

Using frost protection measures reduced the number of years with yields below 20 t/ha in mature orchards. In the Rhineland, the strongest effect was found for using overhead irrigation, which reduced the proportion of years with yields below 20 t/ha from 12% (without protection) to 5%, with a median annual yield of 42.9 t/ha (Q5: 19.8 t/ha; Q95: 60.5 t/ha). Only using portable gas heaters did not decrease the number of years with yields below 20 t/ha in the Rhineland. In the Lake Constance region, all frost protection measures except for the gas heaters reduced the number of years with yields below 20 t/ha. The most effective way to prevent low yields was overhead irrigation, which reduced the share of years with yields below 20 t/ha from 24% (without protection) to 12% with a median yearly yield in mature orchards of 41.8 t/ha (Q5: 9.6 t/ha; Q95: 59.7 t/ha).

3.5. Expected value of perfect information

Overall, due to the remaining uncertainty regarding the best option, investing in reducing parameter uncertainty is more valuable for orchards in Lake Constance than in the Rhineland. The positive EVPI values range from 0.07 €/ha for the number of heaters needed per ha to 1625.55 €/ha for frost risk at Lake Constance (Tab. 2).

There were no positive EVPI values related to tractor-mounted gas heaters, portable gas heaters and below-canopy irrigation. This indicates that given the costs and benefits, these options are currently not a worthwhile investment.

4. Discussion

In our simulations, each individual model run represents a possible combination of risks, costs and returns. In most scenarios and model runs, the apple yield could be increased by investing in frost protection (Supporting Information 8), so that the investment and production costs were spread over a greater production volume. Excluding initial investment, several frost protection measures (overhead

Table 2: Expected Value of Perfect Information (EVPI) [€/ha] for the decision to invest in active frost protection measures in apple orchards in the Rhineland and Lake Constance regions.

Scenario	Option	Variable	EVPI [€/ha]
Rhineland	Candles	Candle places per ha	0.56
	Stationary wind machine	Mean yield loss due to frost [%]	54.58
		Frost protection efficiency of wind machines [%]	13.99
		Number of frost nights during blossom in a year with frost	4.69
Lake Constance	Candles	Candle places per ha	0.82
	Mobile wind machine	Price mobile wind machine	2.25
	Heaters	Heaters needed per ha	0.07
	Overhead irrigation	Frost risk [%]	758.30
		Mean yield loss due to a frost night [%]	285.71
		Mean apple yield [kg/ha]	42.82
		Risk of excessively windy weather [%]	12.35
	Stationary wind machine	Frost risk [%]	1625.55
		Mean yield loss due to a frost night [%]	1167.20
		Mean protection efficiency wind machine [%]	1161.53
		Number of frost nights during blossom in a year with frost	559.80
		Area that can be protected by one stationary wind machine [ha]	408.72
		Mean apple yield [kg/ha]	323.95
		Risk of ineffective protection – stationary wind machine [%]	173.84
		Discount rate	144.44
		Risk of starting the protection too late [%]	76.13
		Installation costs – stationary wind machine [€]	26.78
		Risk of missing to use the protection [%]	21.74
		Risk of damage due to use of wind machines in unfavorable weather conditions [%]	16.79
		Apple price increase in frost years [€/kg]	16.09
		Costs for the building permit – stationary wind machine [€]	12.85
		Risk of technical failure – stationary wind machine [%]	9.87
		Mean apple price [€/kg]	6.87
		Frost monitoring costs [€/year]	6.33
		Production cost change in frost years [%]	6.00
		Price stationary wind machine [€]	5.79
		Hourly wage [€/worker]	5.74
		Year to year variability of the apple price [%]	4.97
		Year to year variability of the risk for unnecessary starting the protection [%]	4.79

irrigation or stationary wind machines in the Rhineland and overhead irrigation, stationary wind machines, mobile wind machines, or below-canopy irrigation at Lake Constance) reduced median production costs per kg apples (Supporting information 6). In most of the model runs, this advantage was not sufficient to cover the investment in the frost protection measure, so that the cost over the whole orchard lifetime increased with frost protection (Fig. 8). The decision to invest in frost protection did not increase the NPV in most cases (Fig. 6).

With stationary wind machines, farmers had the highest chance (46% in Lake Constance region and 25% in the Rhineland) of making a profit from the investment, i.e. increasing the NPV over the orchard lifetime. This was followed by overhead irrigation, with a 32% chance of making profit at Lake

Constance and 15% in the Rhineland. The frost protection efficacy of these two options, which is an important determinant of profitability (Fig. 5), was estimated as high by the experts at 60% to 99% for overhead irrigation and 20% to 80% for the wind machine (Supporting Information 1).

EVPI values indicate that it would be worthwhile to invest up to 1,625.55 €/ha to reduce the uncertainty regarding the variable *frost risk* in the Lake Constance region (Tab. 2). Investing in further research on the variables *mean yield loss due to frost* (up to 1,167.20 €/ha), *frost protection efficiency of wind machines* (up to 1,161.53 €/ha) and further variables in Table 2 could enhance the clarity of investment recommendations.

Mobile wind machines are less effective than stationary wind machines (Beyá-Marshall et al., 2019). In the model, this is expressed as a higher risk that the protection is ineffective during a frost night e.g. due to wind (10-75% for mobile wind machines vs. 10-33% for stationary wind machines; Supporting information 1). Since a single mobile wind machine can protect a smaller area than a stationary one (estimated at 2-5 ha for mobile wind machines vs. 4-6 ha for stationary wind machines), it was necessary in many simulation runs to purchase two mobile wind machines to protect the 4 ha area under investigation. This means that the median investment costs for mobile wind machines of 20,552 €/ha (Q5: 9,323 €/ha; Q95: 31,907 €/ha) in the Rhineland were only slightly lower than for stationary wind machines, which cost 21,117 €/ha (Q5: 18,101 €/ha; Q95: 26,351 €/ha), despite lower purchase costs per machine. Therefore, the *mean area protected by one wind machine* and the *mean mobile wind machine price* were high-VIP variables in the prediction of the profitability of the investment decision (Supporting information 3). Over the whole orchard lifetime and in mature orchards, the production costs per kg apples with mobile wind machines were similar or slightly higher than for stationary wind machines (Fig. 8, Supporting information 6). Furthermore, the increase in accumulated yield over the orchard lifetime was lower than with the stationary wind machine (Fig. 9), so the mobile machines performed worse in this comparison than the stationary wind machines. Some fruit growers have installed stationary wind machines on trailers (Baab et al., 2016). Such self-built mobile wind machines should be considered as stationary ones, in the sense of the decision model, even if the *risk of missed preparation* (value: 1-20%; 90% confidence interval) is not considered then. A further advantage of wind machines, according to the experts, is that the leaves dry out more quickly, which reduces the risk of disease infections.

Below-canopy irrigation systems are mainly suitable for light frosts (Snyder and Melo-Abreu, 2005a). This is considered in the model inputs through low protection efficacy, which the expert group estimated at 10% to 50%. The increase in median accumulated yield over the orchard lifetime of 3% in the Rhineland and 4% in the Lake Constance region compared to apple production without frost protection was considerably lower than with overhead irrigation, which led to increases of 7% in the Rhineland and 12% in the Lake Constance region. Thus, overhead irrigation performs better in our economic comparison due to its higher efficacy, although the median investment cost for below-canopy irrigation of 22,532 €/ha (Q5: 17,847 €/ha; Q95: 29,026 €/ha) is lower than for overhead-irrigation (median: 26,970 €/ha, Q5: 21,427 €/ha, Q95: 34,196 €/ha) in the Rhineland (Supporting information 7). A positive side effect of both irrigation systems is that the main components of the infrastructure (pond, pump etc.) could be used for irrigation in summer as well. Overhead irrigation systems can also be applied for evaporative cooling to reduce sunburn damage (Racsko and Schrader, 2012). In our simulation, we assume that the main reason for drilling a well and building an irrigation pond is the use for frost protection, i.e. we count all investment costs as costs for frost protection. Fruit growers may build such infrastructure for irrigation in drought periods and for frost protection. In this case, the costs could be split between the two purposes, which would increase the profitability of the investment option. The same applies if a suitable well and/or pond already exists on the farm and only some of the additional infrastructure needs to be purchased.

Tractor-mounted and portable gas heaters are comparatively inexpensive, with initial investment of 8,476 €/ha (Q5: 3,765 €/ha; Q95: 13,869 €/ha) and 6,498 €/ha (Q5: 4,348 €/ha; Q95: 12,386 €/ha), respectively. The protection efficacy of these measures was controversially discussed in the expert group. It was estimated as low at 1% to 20% for portable gas heaters and 3% to 50% for tractor-mounted gas heaters (Supporting information 1). The experts also reported problems with the browning and burning of leaves and flowers as described by Baab et al. (2016). The resulting damage is incorporated in the model as a risk. The chances of an economic advantage with gas heating systems are not particularly high, with a maximum of 18% for the tractor-mounted model in the Lake Constance region. Still, there is also no risk of large losses, as can occur with pellet heaters or candles (Fig. 6). The use of candles as a regular frost protection measure may lead to median NPV losses compared to production without frost protection of 84,775 €/ha (Q5: 30,359 €/ha; Q95: 186,212 €/ha) in the Rhineland and 103,764 €/ha (Q5: 36,034 €/ha; Q95: 227,225 €/ha) in the Lake Constance region. A major cost factor is storage of the candles, described through the variables *mean storage costs per candles, recommended number of candles in storage* and *number of candles needed per ha* (Supporting Information 3). It is recommended to store 3 to 6 candles per candle location in the orchard to prepare for frost during the weekend or for limitations in candle supply. The labor that is required to protect the orchard with candles also depends on the number of candles needed per ha. Therefore, investing 0.56 €/ha (Rhineland) to 0.82 €/ha (Lake Constance region) in more precise knowledge about the optimal number of candles could be helpful for the decision (Tab. 2). The number of candles per ha is a critical factor because it influences the workload and efficacy of frost protection (Lakatos and Brotodjojo, 2022). Despite the high costs, candles can be an interesting option in some cases because they contribute to securing yields as they increase the yield compared to the 'no protection' scenario in 87% of the model runs for the Rhineland and in 94% of the model runs for the Lake Constance region.

Like candles, the number of pellet heaters per ha also plays a major role in the projection of the NPV of the investment decision (Tab. 2, Supporting Information 3). Despite the slightly lower estimated frost protection efficacy (Supporting Information 1), which results in a smaller yield effect (Fig. 9), the pellet heaters performed slightly better than the candles in the economic comparison due to lower costs (Fig. 6, Fig. 8).

The two apple production regions to which our model was applied differ mainly in the main way of selling the apples and the frost risk. The differences in the marketing channel are included in the inputs. Rhineland markets require more processing by the farmer, which drives up production costs per kg (Fig. 8). The model results indicate that the investment in frost protection is more likely to be an economic advantage in the Lake Constance region (Fig. 6), where the number of harmful frost nights is greater (Fig. 4). This is also apparent in the high and positive correlation of the input variable *frost risk* with the economic advantage of the frost protection measures compared to the 'no protection' scenario (Fig. 5).

Unterberger et al. (2018) also found that the number of frost nights had an influence on which frost protection measure was most profitable. In contrast to our results, using heaters was found to be the most economically viable option, but only when frost events are rare (Unterberger et al., 2018).

Contrary to our results, Fike et al. (2020) computed positive NPV for several active frost protection measures based on a deterministic model. Their assumptions for the initial investment costs were 7,450 €/ha for overhead irrigation and 7,000 €/ha for wind machines in Slovenia, which is considerably lower than our calculations of 26,975 €/ha (Q5: 21,399 €/ha; Q95: 34,194 €/ha) and 21,117 €/ha (Q5: 18,101 €/ha; Q95: 26,351 €/ha), respectively, for the Rhineland and similar values for the Lake Constance region. A database developed by Snyder and Melo-Abreu (2005b) concurs with our model. They found that wind machines with internal combustion engines show the best economic performance if not more than 2°C of protection are needed. For locations where stronger frosts occur, using overhead sprinklers was identified as the most profitable measure (Snyder and Melo-Abreu, 2005b).

Thanks to their yield and fruit quality effects (e.g. frost protection, water supply, sunburn protection), frost protection measures can make an important contribution to securing regional apple production and help stabilize the level of self-sufficiency for apples in Germany. Besides overhead irrigation and stationary wind machines, candles are also an effective option in terms of yield protection (Fig. 9). However, the use of candles is not adviseable due to the considerably worse economic result (Fig. 6).

Extreme frost events, such as the severe frost in 2017, are not limited to Germany but also affect fruit production in neighboring countries (Faust and Herbold, 2017; Vitasse and Rebetez, 2018). As forecasts based on climate models show that late frost will continue to be a relevant problem in the near future (Hoffmann and Rath, 2013), increasing the area with frost protection can be a critical contribution to securing apple production in the future. (Further) financial support for investment in frost protection measures can also help make their use economically attractive for fruit growers. Measures that have a reliable protective effect (Fig. 9) and at the same time perform well economically (Fig. 6, Fig. 8), such as wind machines and irrigation systems, are particularly suitable for a funding program. The size of possible grants should then be sufficient to cover the gap between the NPV with and without frost protection, i.e. to make the NPV advantage of the measures compared to the 'no protection' scenario (Fig. 6) positive. To achieve this, a median amount of 1,109 €/ha would be sufficient to support the use of stationary wind machines at Lake Constance, but a median value of 18,332 €/ha would be needed to make below-canopy irrigation in the Rhineland profitable compared to the 'no protection' scenario in the majority of cases (Fig. 6). For the irrigation options, this support should be offered in addition to the existing financial support measures, while for wind machines, this could be a stand-alone measure.

Our model provides an overview of the performance of frost protection measures based on value ranges that cover the entire Rhineland and Lake Constance regions and the assumption of a predominant marketing channel. To draw conclusions for individual fruit growers, many variables related to on-farm conditions would need to be considered. This includes, for example, the local frost risk (e.g. valleys or cold spots) and predominant frost type (radiation or wind frost), water availability, and funding opportunities (e.g. for young farmers), as well as the markets for apples. In our model, we have not accounted for intangible benefits of protecting orchards from frosts. These might include delivery reliability, personal well-being of the fruit grower or reduction of alternate-bearing. If these are included as part of the benefit of frost protection, some of the options might look considerably better.

Although our model does not cover all available frost protection measures and individual farm situations, it can still be widely applied to other similar problems. By including our uncertainty about all important input factors, we offer the possibility of adjusting related input parameters so that our model can be adapted to other marketing channels, locations, changing situations, and other tree fruit species.

Our model input variable *frost risk* (for future years) is based on expert estimates made with the help of historical data. As the frost risk is an important variable in the calculation of frost protection profitability (Fig. 6) and has a high EVPI for the options *stationary wind machine* and *overhead irrigation* in the Lake Constance region (Tab. 2), further research should look at the development of frost risk under different future climate scenarios. Our decision model could then be used to project protection profitability for future scenarios. It may also be worth exploring the combination of several protection measures, e.g. wind machines and below-canopy irrigation, as they may have combined advantages regarding protection effectiveness and economic performance.

5. Conclusion

Through an innovative model-based forecasting approach, we show how active frost protection measures differ in their economic performance and yield protection efficacy. For the two regions under investigation, overhead irrigation and stationary wind machines were the most promising options. Nevertheless, the increased yields from frost protection could not always cover the investment costs. The simulation results show that investments in frost protection are more promising in the Lake Constance region where the risk of frost is higher than in the Rhineland. The results offer guidance to apple growers making decisions about frost protection. The result also alert policymakers to the importance of supporting frost protection to ensure regional apple production in changing climatic and economic situations. Our approach allowed us to include uncertainty regarding the input variables in the modeling process. The method is particularly useful for handling variables such as frost risk that are hard to measure with ordinary measuring devices and have a high importance for the model outcome. Our method provides a robust framework for effectively managing uncertainties inherent in agricultural and environmental decision-making processes, facilitating informed choices and enhancing resilience across diverse contexts within these sectors.

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CRediT authorship contribution statement

C. Schmitz: Writing - original draft, Investigation, Visualization, Software; L. Zimmermann: Writing - review & editing, Investigation; K. Schiffers: Writing - review & editing, Supervision; C. Whitney: Writing - review & editing, Methodology; M. Balmer: Writing - review & editing, Conceptualization, Funding acquisition, Supervision; E. Luedeling: Writing - review & editing, Conceptualization, Methodology, Supervision

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Chapter 6: Spatially explicit forecasting of frost damage in German apple cultivation under changing climatic conditions

Under review in Agricultural Forestry and Meteorology

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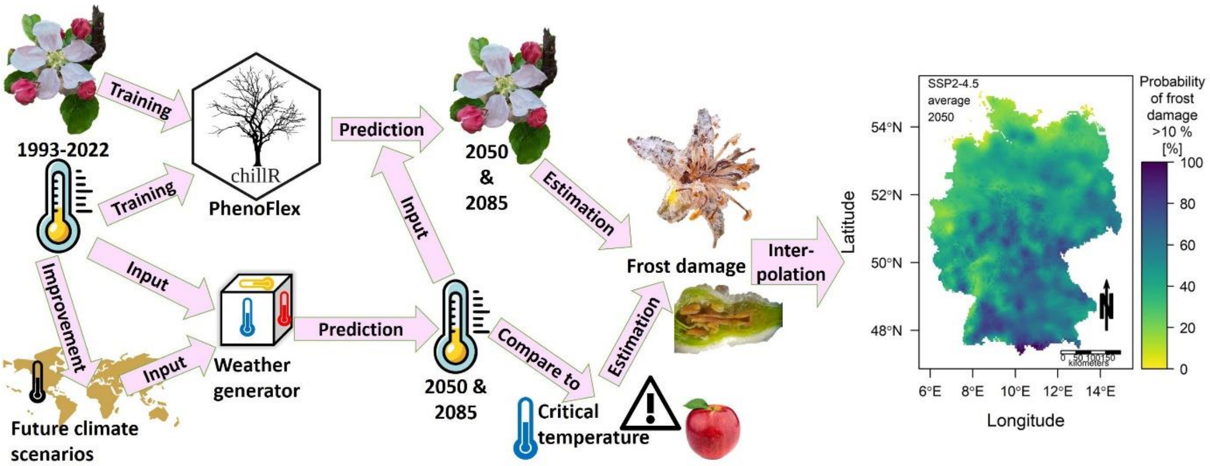
Graphical Abstract



Abstract

Late spring frosts repeatedly cause significant yield reductions and economic losses for apple producers. Observations from recent decades show a trend toward earlier apple flowering and an increasing risk of frost damage in Germany. This raises the question of how frost risk will develop in the future. To address this question, we used weather data and crowd-sourced phenological observations from 1993 to 2022 to train the phenology prediction model PhenoFlex. Based on predicted phenological stages and critical temperature thresholds, we estimated the probability of frost damage for the future periods 2050 and 2085 under four climate scenarios (SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5). For the timing of phenological stages preceding bloom, we estimated stage-specific shares of the trees' heat requirements that had to be fulfilled. We assessed the probability of frost damage at 3350 locations across Germany and interpolated the results to produce frost damage risk maps for Germany.

The forecast results indicate that the trend toward earlier apple blossom will continue across all climate scenarios. However, we detected regional differences in the effect on frost risk around mid-century. Toward the end of the century, the probability of frost damage decreases at most locations compared to 1993–2022, with greater reductions under more severe climate scenarios. Despite these changes, late spring frost will remain a challenge for apple production in Germany throughout the 21st century. The generated maps can assist farmers deciding on investments in frost protection measures, and they can provide information to policy-makers aiming to develop support measures for the fruit sector.

1. Introduction

Late spring frosts are a common problem in the production of tree fruit in Central Europe. Extreme events like the frost in April 2017, which caused about 3.3 billion euros of damage across Europe (Faust and Herbold, 2017), can be disastrous for fruit growers. Frost damage is usually caused by the formation of ice crystals in the extra-cellular space, which leads to dehydration of the plant cells or physical damage of membranes and tissues (Burke et al., 1976; Rodrigo, 2000). Although plants have developed various adaptations to withstand frost temperatures, such as “supercooling” or the accumulation of osmotically active substances, frost can damage buds, flowers and young fruits, which is particularly detrimental to the production of tree fruits (Hillmann et al., 2020).

For German fruit growers, the risk of spring frost damage in apple production is particularly critical, as apples dominate national fruit cultivation and are highly vulnerable to frost-related yield losses. In 2024, apples were grown on 32,990 ha, which is about 45% of the German fruit production area (Destatis, 2025; Garming, 2023). The frost sensitivity of apple floral buds increases as the phenological development progresses (Ballard et al., 1981; Proebsting and Mills, 1978). The critical temperatures for 10% kill of apple flower buds range from -7.8 °C during the green tip stage to -2.2 °C at bloom (Ballard et al., 1981). Buds affected by frost can either be shed or develop into fruits that show signs of frost damage, e.g. by exhibiting an unusual shape, appearance or size (Rodrigo, 2000). In addition, the internal quality of the apple fruits can be affected (Cebulj et al., 2021), and there is a risk of intensified alternate bearing in the following years, starting with an extreme “off” year in the frost year and an “on” year in the following year (Büchele, 2018). These effects on yield and quality strongly reduce the overall revenue from an orchard (Dalhaus et al., 2020). Knowledge about the future frost risk is therefore important for operational planning, e.g. for decisions on investments in frost protection measures (Schmitz et al., 2025b).

Over the last few decades, a trend toward earlier blossom has been observed, not only for apples (Weil et al., 2018) but also for other tree fruit species including pears (Kunz and Blanke, 2022) and cherries (Waldau and Chmielewski, 2018). At the same time, the frequency of late frosts, described as the number of days with temperatures below 0°C in April, has increased (Kunz and Blanke, 2022). Due to climate change, the change in temperatures and apple phenology is expected to continue in the future. Hoffmann and Rath (2013) predicted a shift toward earlier apple blossom by around 12.9 days by 2085 compared to the 1971-2000 period. The consequence of climate change for future frost risk has so far only been investigated for individual locations and regions in Germany. Depending on the region and the climate model, an increase (Pfleiderer et al., 2019) or decrease (Hoffmann and Rath, 2013) in the frequency of late frosts is predicted.

The PhenoFlex modeling framework allows forecasting spring phenology of temperate fruit trees (Luedeling et al., 2021). It has been successfully applied to predict the bloom date of apple trees (Fernandez et al., 2022). In combination with a weather generator and future climate projections from the 6th phase of the Coupled Model Intercomparison Project (CMIP6), PhenoFlex has been used to forecast the future bloom dates of almonds in California (Caspersen et al., 2024). Bosdijk et al. (2024) combined PhenoFlex with a frost damage model and showed that the risk of spring frost damage in Dutch apple production will increase in the coming years, but decrease in the long term. Ford et al. (2025) used the same model to predict future changes in frost damage risk for apples in the Midwest region of the United States, finding that, despite advancing spring phenology, significant increases in frost risk appear unlikely.

Apples are not only the most important tree fruit in commercial production (Destatis, 2025; Garming, 2023); they also grow in orchard meadows (Henle et al., 2024) and home gardens all over the country. Nevertheless, to date there are no countrywide maps of the frost risk in German apple production.

Previous studies have focused on specific locations (Pfleiderer et al., 2019) or a single federal state (Hoffmann and Rath, 2013). In addition, these studies concentrate only on frost events during and after bloom, neglecting sensitive phases that occur earlier in the season. This issue was recently addressed by Bosdijk et al. (2024), who developed an approach to consider the phenology stages before apple bloom in a frost risk forecast for the Netherlands.

Building on the work of Bosdijk et al. (2024), we developed an extended approach to produce countrywide maps of future spring frost risk in Germany, taking into account the sensitive phenology stages before bloom. To predict future apple phenology, we fitted the PhenoFlex model with historical temperature data and crowd-sourced apple bloom dates. We estimated the probability of frost events exceeding damage thresholds of 10% and 50% for two future periods (2050 and 2085) and several climate projections. We interpolated the results gained at the station locations to provide countrywide maps of future spring frost risk for apples.

2. Materials and methods

2.1. Study area

We focused on Germany, where the climate is characterized by year-round precipitation, relatively mild winters and moderately hot summers, due to prevailing winds from the west which bring wet humid air masses to the country (Müller-Westermeier, 2002). The climate in the north-west of Germany is rather oceanic, whereas toward the southwest the climate shows an increasingly continental influence (Leibniz-Institut für Länderkunde, 2003). The topographical structure, with the Alps in the south and several lower mountain ranges all over the country (Figure 1), leads to small-scale climatic structures within the country (Müller-Westermeier, 2002).

2.2. Phenology, weather and elevation data

We used publicly accessible crowd-sourced apple phenology data from the years 1993 to 2022 provided by the German National Meteorological service (Deutscher Wetterdienst (DWD), 2023a, 2023b; DWD Climate Data Center (CDC), 2023a, 2023b) for our modeling. Apple phenology observations were made by volunteer phenology observers following a standardized protocol. The phenology observations are sorted into early- and late-ripening varieties. Around two thirds of the reports on early-ripening varieties are for the cultivar 'Klarapfel' and 45% of reports on late-ripening varieties for 'Boskoop' (Deutscher Wetterdienst (DWD), 2021). From all available data for those two ripening periods, we selected the records for the start of bloom (BBCH 60, based on the BBCH scale for plant growth stages developed by the Biologische Bundesanstalt, Bundessortenamt, and the Chemical Industry (Meier et al., 1994)). The number of locations with phenology observations was between 742 and 2034 per year, depending on year and ripening time, and decreased over time. In total, we used 69,990 (33,062 early-ripening, 36,928 late-ripening) records for the start of apple bloom from 3350 locations (Figure 1).

We obtained daily minimum and maximum temperatures for the years 1992-2022 from the German National Meteorological Service (Deutscher Wetterdienst (DWD), 2023c). The temperatures were measured at 2 m height and were available from 446-568 weather stations per day. The locations of the weather stations ensure good coverage of the entire country (Figure 1). We used land surface elevation data (in meters above sea level (m a.s.l.)) from a publicly accessible digital elevation model of Germany with a resolution of 1 m (OpenDEM, 2011) as explanatory variable for the interpolation steps.

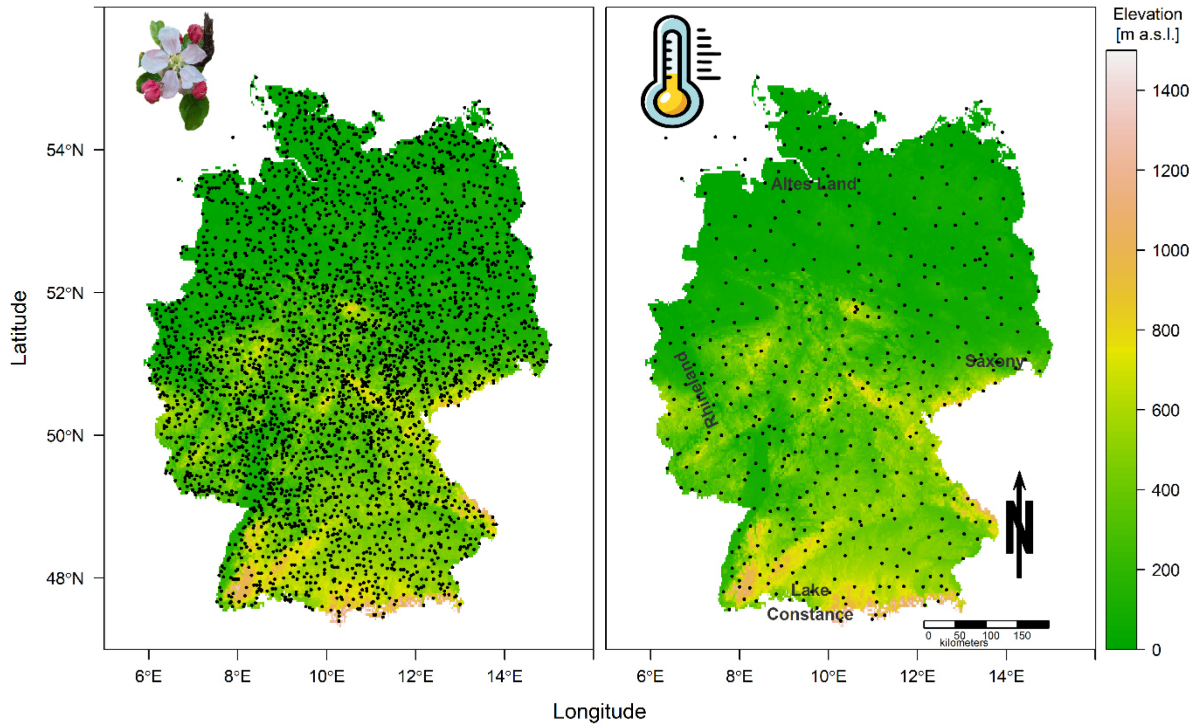


Figure 1: left: locations of phenology stations with a least one observation for the start of apple bloom in the years 1993-2022; right: weather stations with observations for daily minimum and maximum temperature on first of January 2022 and locations of the four main apple production regions in Germany. The background displays land surface elevation in meters above sea level (m a.s.l.) (Source of elevation data: OpenDEM (2011)).

2.2.1. Interpolation of weather data to the locations of the phenology records

Since the phenology observations were not necessarily located at weather stations, we used regression Kriging to estimate the weather conditions at the exact locations where bloom dates were recorded. This was done using the STIF Python package (Kopton, 2024). We used a two-step approach: first, we performed linear regression to exploit correlation with elevation and latitude as covariates. This allowed accounting for elevation-related differences in temperature, even at high elevations for which no direct observations were available. This adjustment improved prediction accuracy compared to pure ordinary Kriging. Second, we used space-time variogram Kriging to exploit spatio-temporal autocorrelation in the temperature data. The regression part was able to explain 5% of the overall variance, indicating that elevation and latitude alone are insufficient for capturing the observed spatial temperature variation. For Kriging, we used a maximum distance of 500 km and 3 days. A product-sum relationship with spherical spatial and temporal components was selected as a space-time variogram model (Venkatachalam and Kumar, 2017). Kriging was performed with a maximum of 50 points. 10-fold cross-validation with 10% of the weather observations randomly selected as validation sets revealed an average coefficient of determination (R2) of 96% and a mean absolute error of 0.62 °C. Since most phenology observations are much closer to the nearest weather station than the weather stations are from each other, we assume the actual interpolation error to be significantly lower.

2.3. Climate projections

In our analysis, we used climate projections from the sixth phase of the Coupled Model Intercomparison Project (CMIP6) (Eyring et al., 2016), which we downloaded from the Climate Data Store (Copernicus Climate Change Service, 2021). These climate projections are available for several combinations of the Shared Socioeconomic Pathways (SSPs) and Representative Concentration Pathways (RCPs). The SSPs describe alternative future global developments: SSP1 stands for a sustainable development, SSP2 describes an intermediate scenario based on typical development patterns in the past, SSP3 assumes increasing regional rivalry, SSP4 stands for inequality between countries and within societies, and SSP5 describes a fossil-fuel driven development (O'Neill et al., 2017). Each SSP is combined with an RCP, which shows the expected future change in radiative forcing ranging from a low forcing level of 2.6 W/m² up to a severe forcing level of 8.5 W/m² (O'Neill et al., 2016; van Vuuren et al., 2011). We made our frost projections for two future time periods: 2035-2065 (called 2050, the middle of the period) and 2070-2100 (called 2085) with the pathways SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5. For each scenario, 16 to 20 General Circulation Models (GCMs) are available for Germany (Supporting Information 1). Since the grids for these scenario/model combinations are of coarse resolution, we calculated the temperature difference between the recent past and future grids and added these differences to the interpolated historical temperatures at the phenology observation sites to obtain more site-specific temperature change scenarios.

To reduce the large number of scenario/model combinations to a manageable number of future projections without losing the full range of possible future climates, we decided to keep all four SSPs, but to use summary statistics to represent the range of available GCMs in the analysis. For each SSP and for both future periods (2050 and 2085), we calculated the 10%-quantile, median and 90%-quantile of all temperature change scenarios generated by the GCMs at each location and used the results as summarized parameters describing the range of available GCMs. We call the summarized GCMs optimistic (10%-quantile), average (median) and pessimistic (90%-quantile) models. For each combination of SSP and summarized GCM, 100 possible temperature scenarios (daily minima and maxima) for the future periods 2050 and 2085 were generated using the RMAWGEN weather generator (Cordano and Eccel, 2016), as implemented in the chillR package for R (Luedeling et al., 2024). Figure 2 provides an overview of all modeling steps in our frost damage projection.

2.4. Prediction of phenological stages

2.4.1. The PhenoFlex model

PhenoFlex is a modeling framework to forecast the spring phenology of temperate fruit trees (Luedeling et al., 2021). It combines the Dynamic Model (Fishman et al., 1987a, 1987b) for chill accumulation with the Growing Degree Hours (GDH) concept (Anderson et al., 1986) for heat accumulation and takes into account that additional chilling may reduce the amount of heat needed for budbreak (Luedeling et al., 2021). Of the 12 PhenoFlex parameters, six relate to the Dynamic Model (E_0, E_1, A_0, A_1, T_f, slope) and three to the GDH Model (T_b, T_u, T_c). Additionally, the model has parameters specifying the chill requirement (y_c), heat requirement (z_c) and the transition from chill to heat accumulation (s_1). The parameters of the model were optimized using temperature and phenology observations. We used the programming language R (R Core Team, 2024) to run PhenoFlex, which is part of the *chillR* R package (Luedeling et al., 2024), and additional functions from the *LarsChill* package (Caspersen, 2025) for parameterization.

2.4.2. Parametrization of PhenoFlex

In order to parameterize the model, we split the available phenology observations into a validation and 10 calibration datasets. Early- and late-ripening varieties were considered separately. To set up the validation dataset, we took 25% of the all observations. From the remaining dataset we randomly drew 10 datasets of 1000 observations each for calibration and fitted PhenoFlex for each of the 10 calibration subsets.

The PhenoFlex model has twelve parameters. We adjusted the calibration process as outlined by Caspersen et al. (2025), by replacing parameters of the chill submodel with intermediate parameters for which plausible ranges can be specified more easily. Furthermore, two parameters were kept constant as they contributed little to model performance (θ^*=279K, T_c=36°C). The remaining 10

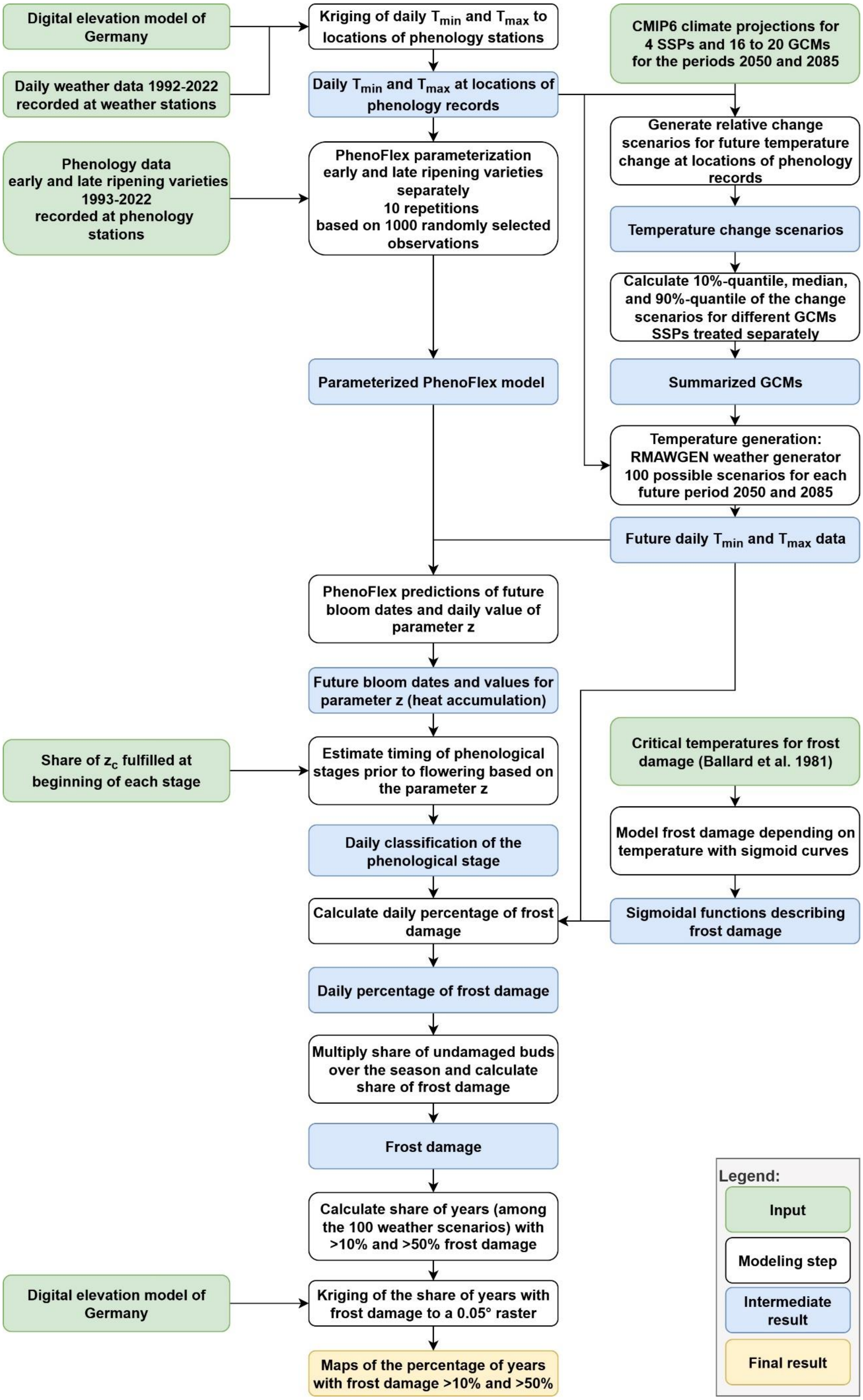


Figure 2: Workflow diagram including all modeling steps to produce maps of future frost damage frequency.

parameters were calibrated using the generalized simulated annealing (GenSA) algorithm (Tsallis and Stariolo, 1996; Xiang et al., 2013). We evaluated the estimated model parameters by calculating the Root Mean Square Error (RMSE), Ratio of Performance to Interquartile Distance (RPIQ) and mean bias (predicted minus observed) for the calibration and validation data. The RPIQ relates the RMSE to the interquartile range of the observed data. Greater RPIQ values indicate better performance and a value greater than 1 indicates that the RMSE is smaller than the interquartile range of the observed data. Since all ten parameterization repetitions (Supporting Information 2) showed similar performance and temperature response (Supporting Information 13), we continued our analysis based on the first repetition. This repetition had an RMSE of 6.3 days and an RPIQ of 1.9 for early- and an RMSE of 6.2 days and an RPIQ of 1.9 for late-ripening apple varieties.

2.4.3. Predictions with PhenoFlex

With the fitted model, we predicted chill and heat accumulation throughout the season and the resulting start of bloom. Chill and heat accumulation can be described by parameters x, y, and z, where parameter x describes the formation of a precursor to the dormancy-breaking factor, y describes the chill accumulation and z the heat accumulation. From the generated future weather at 3350 locations (Figure 1), we took the daily temperature minima and maxima as well as the latitude of the stations to generate hourly temperatures. To this end, we combined the daily temperatures with an idealized daily temperature curve constructed from information on site- and date-specific sunrise and sunset times (Luedeling et al., 2013).

For both model parameterizations (early- and late-ripening apple varieties), the four SSPs and the three models, we calculated x, y and z based on the hourly temperatures.

2.4.4. Estimation of stages preceding bloom

We estimated the timing of phenological stages prior to flowering by calculating the heat requirement for each stage relative to the calibrated heat requirement for flowering z_c, following the approach outlined by Bosdijk et al. (2024). We estimated the need of heat accumulation for the phenology stages 'green tip', 'half inch green', 'tight cluster', 'first pink', 'full pink' and 'start of bloom' based on observations by Chaves et al. (2017) for the apple cultivars 'Cripps Pink', 'Gala' and 'Red Delicious' (Table 1).

For each day in the future predictions, we checked if the parameter z fulfills the requirement for the next stage (i.e. z is larger or equal to z_c * share of z_c fulfilled at the beginning of a stage) and assigned the current stage accordingly.

We evaluated the prediction of the green tip stage by calculating the RMSE and the RPIQ of the predicted start date of this stage compared with observed dates in the recent past (1992-2022). The prediction for start of the green tip stage had an RMSE of 17.8 days for early- and 22.5 days for late-ripening varieties. The RPIQ was 1.0 and 0.8, respectively.

2.5. Estimating frost damage

We used critical temperatures reported by Ballard et al. (1981) as a foundation for our frost damage forecast. The critical temperatures are available for 10% and 90% flower bud kill rate (Ballard et al., 1981). As the real frost damage may be any value between 0 and 100%, we modeled the frost damage for all negative temperatures using a sigmoid curve. The sigmoid curves (Equation 1, Figure 3) for each phenology stage were fitted using the Nelder-Mead method (Nelder and Mead, 1965), based on the average temperature for 90% flower bud kill rate, the average temperature for 10% flower bud kill rate and the zero point. L is the upper asymptote of the curve and is set to 1, which corresponds to 100% frost damage. The factor k is the steepness of the curve and x_0 describes the midpoint of the curve in °C.

$frost_{damage}(x) = \frac{L}{(1+e^{-k*(x-x_0)})}$ (Equation 1)

For each day in all future weather scenarios with a minimum temperature below 0°C and a phenology stage of 'green tip' or further developed, we inserted the observed minimum temperature (x) into the fitted function to calculate the expected frost damage. We used a stepwise approach for the phenological stages, i.e., we used the same curve to describe frost damage for a bud at the beginning and end of a stage. Based on the expected frost damage, we calculated the share of undamaged buds, flowers, or young fruits after each night. To determine the share of undamaged young fruits by the end of June, we multiplied the daily shares of undamaged apples for each day of the season (start of green tip stage until end of June). We assumed that a previous frost event has no effect on sensitivity to a subsequent frost event.

Table 1: Important model parameters for different phenology stages in spring. The share of z_c describes the share of heat accumulation that has to be reached to enter the stage. The average temperature for 10% and 90% flower bud kill rate were used to fit sigmoid curves of frost damage described by the parameters k for the steepness of the curve and x_0 for the midpoint of the curve in °C.

Pheno-logy stage	BBCH stage	Share of z_c fulfilled at the beginning of the stage [%]	Average temperature for 10% flower bud kill rate according to (Ballard et al., 1981) [°C]	Average temperature for 90% flower bud kill rate according to (Ballard et al., 1981) [°C]	Fitted value for k	Fitted value for x_0
Green tip	53: bud burst	25	-7.8	-12.2	-0.999	-10.000
Half inch green	54: mouse-ear stage	37	-5.0	-9.4	-0.999	-7.201
Tight cluster	55: flower buds visible	58	-2.8	-6.1	-1.332	-4.450
First pink	57: red bud stage	70	-2.2	-4.4	-1.998	-3.300
Full pink	59: balloon state	86	-2.2	-3.9	-2.585	-3.050
Start of bloom	60: first flowers open	100	-2.2	-3.9	-2.585	-3.050
Blossoms and young fruits	61: 10% flowers open and later	/	-2.2	-3.9	-2.585	-3.050

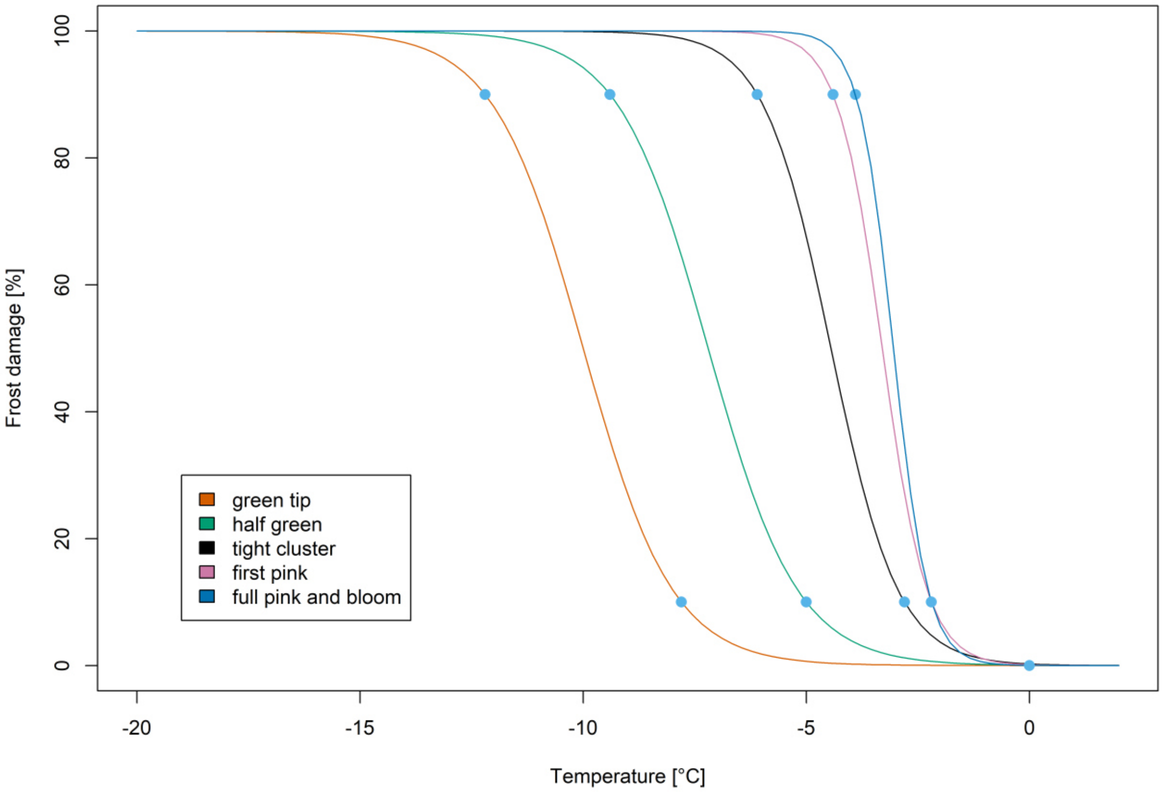


Figure 3: Sigmoidal curves describing frost damage when apple buds and blossoms are exposed to freezing temperatures. The color of the curves indicates the phenological stage for which they are valid. The curves were fitted based on data for 10% and 90% flower bud kill rate (Ballard et al., 1981) and the assumption that no damage occurs above 0°C, shown as red dots.

2.6. Summarizing and interpolating frost damage

We summarized the expected frost risk by calculating the probability of frost damage based on the frequency of cases with any damage, with damage >10% and damage >50% in the 100 weather scenarios.

For each SSP, summarized GCM and ripening time, we used regression Kriging (also known as "Kriging with external drift") to spatially interpolate the probability of years with frost damage (>10% and >50%) for the future periods 2050 and 2085. Again, we used elevation data extracted from a digital elevation model of Germany (OpenDEM, 2011) as explanatory variable (Figure 1).

To describe the relationship between the probability of frost damage and elevation, we fitted shape-constrained additive models (Pya and Wood, 2015). This model type allows stipulating a monotonous relationship between the explanatory and dependent variables, which reduces the risk of overfitting and unexpected behavior. Spherical variogram models (with nugget) were fitted to the regression residuals of the additive models using the ordinary least squares fitting method. Based on these variogram models, we conducted ordinary Kriging on a raster grid with a 0.05° cell size (approximately 3.5 × 5.5 km), using up to 15 Kriging points. We used functions from several R packages, mainly *gstat* (Pebesma, 2004), *terra* (Hijmans, 2023), *stars* (Pebesma and Bivand, 2023) and *scam* (Pya, 2023) to interpolate the results. The maps were produced with the *rasterVis* package (Perpi and Hijmans, 2023). Supporting Information 3 provides a full overview of all packages used in our code. The code used for model parameterization, phenology predictions, frost risk estimation and interpolation, as well as the main results are available on Zenodo (Schmitz et al., 2025a).

2.7. Estimating frost risk in the recent past

We applied the process of PhenoFlex predictions for x, y, z and start of bloom, estimating earlier stages and calculating expected frost risk also to the interpolated historical weather data (1993-2022). This allows comparing the recent past with the future predictions

3. Results

3.1. Frost frequency in the recent past

Applying PhenoFlex and the frost damage estimation procedure to the recent past (1993 to 2022) showed that frost events occur almost all over Germany (Figure 4 and Figure 5). In the recent past, the frequency of frost events with more than 10% damage ranged between 0% and 86% (median 49%) for early-ripening varieties and 0% and 87% (median 50%) for late-ripening apple varieties depending on the raster cell. In 50% of the raster cells covering Germany (i.e. half of the country area), the damage rate was between 33% and 60% for early- and between 36% and 60% for late-ripening varieties. The regions with the lowest frost damage frequency were located in the North of Germany along the North Sea and Baltic Sea coasts (Figure 4).

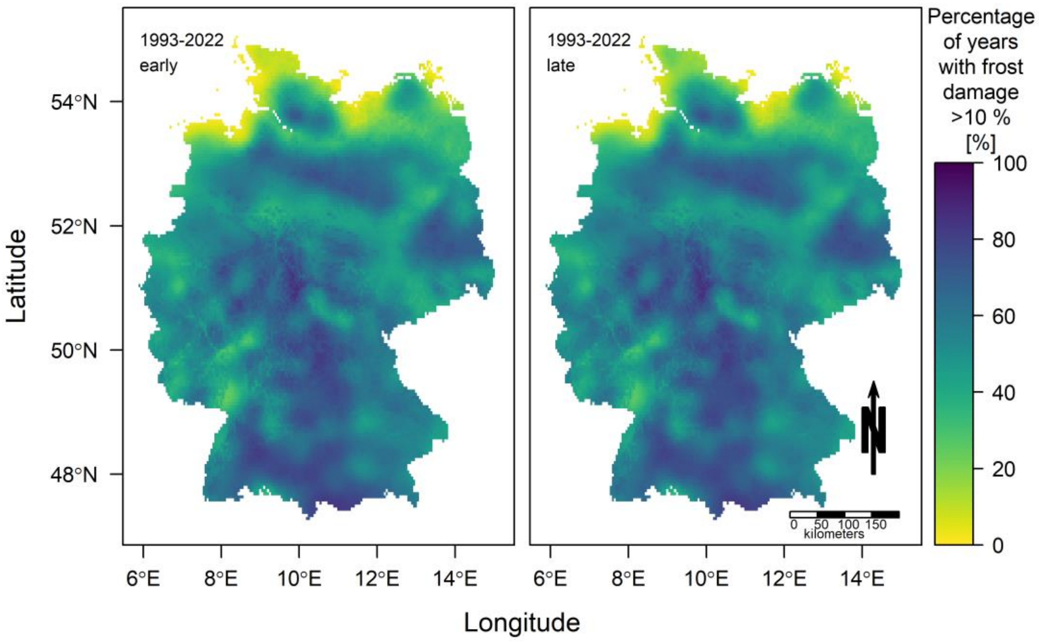


Figure 4: Estimated percentage of years with frost damage affecting more than 10% of the buds, flowers and young apple fruits during the years 1993-2022 in Germany for early-ripening (left) and late-ripening (right) apple varieties. Maps are based on interpolated data for the percentage of years with frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

Severe late frosts in spring, causing damage to more than 50% of apple buds, blossoms and young fruits, occurred much less frequently. In half of the raster cells covering Germany, the frequency of frost damage >50% for early-ripening varieties ranged between 11% and 33% (median 24%). However, the location with the highest frost frequency, located in the Alps, experienced severe frost in 75% of the years. Similar results were found for late-ripening varieties, with a maximum of 76% of the years featuring more than 50% damage. The frequency of severe damage on late-ripening varieties lay between 12% and 33% (median 23%) of the years in half of the grid cells. Similarly to the frequency of frost damage >10%, the lowest frequency of frost damage >50% was found along the coast. High frequencies of late frosts causing more than 50% damage during the susceptible stages of apple development were observed in central Germany and near the Alps in the South (Figure 5).

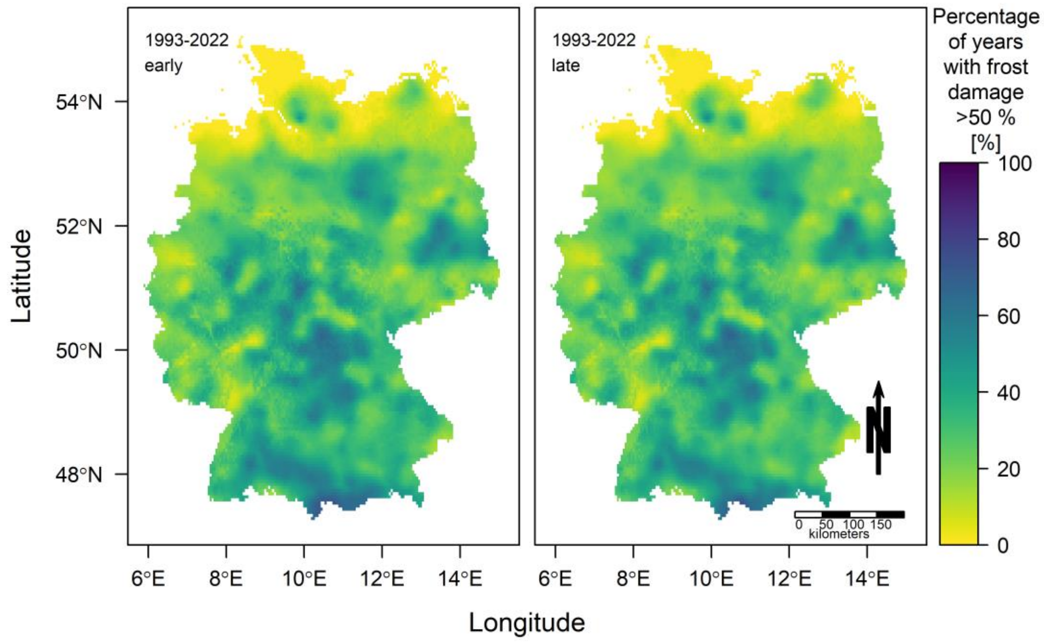


Figure 5: Estimated percentage of years with frost damage affecting more than 50% of the buds, flowers and young apple fruits during the years 1993-2022 in Germany for early-ripening (left) and late-ripening (right) apple varieties. Maps are based on interpolated data for the percentage of years with frost damage >50% and have a cell size of 0.05° (about 3.5x5.5 km)

3.2. Bloom date shift

All over Germany, apple bloom started on average on April 27th (Day of the year (DOY) 117) for early-ripening and on April 30th (DOY 120) for late-ripening varieties in the period 1993-2022. Our phenology predictions for all SSPs and the summarized GCMs showed a trend toward earlier apple bloom in 2050 and 2085 compared to the recent past (Figure). This means, for example, that the median date of the beginning of apple bloom (for an early-ripening variety) is expected to be 10.9 days earlier in 2050 compared to 1993-2022 if the climate changes as expected in SSP2-4.5 with the average model. In 2085 the median bloom date under these conditions will be three additional days earlier.

In most cases, this trend is expected to continue between 2050 and 2085. Only for the most extreme change scenario SSP5-8.5 with the pessimistic model, the trend was reversed and the median bloom date was predicted to be 3.4 days later for early- and 1.1 days later for late-ripening varieties in 2085 compared to 2050.

Using different GCMs leads to large differences in the predicted start of bloom for all SSPs in 2050. For example, the median start of bloom in SSP3-7.0 differs by 12.3 days for early-ripening varieties and 13.0 days for late-ripening varieties between the optimistic model (climate models predicting slight temperature change) and the pessimistic model (climate models predicting strong temperature change). In 2085, the differences caused by the spread between the different GCMs are considerably smaller, especially for the more severe change scenarios SSP3-7.0 and SSP5-8.5 (Figure).

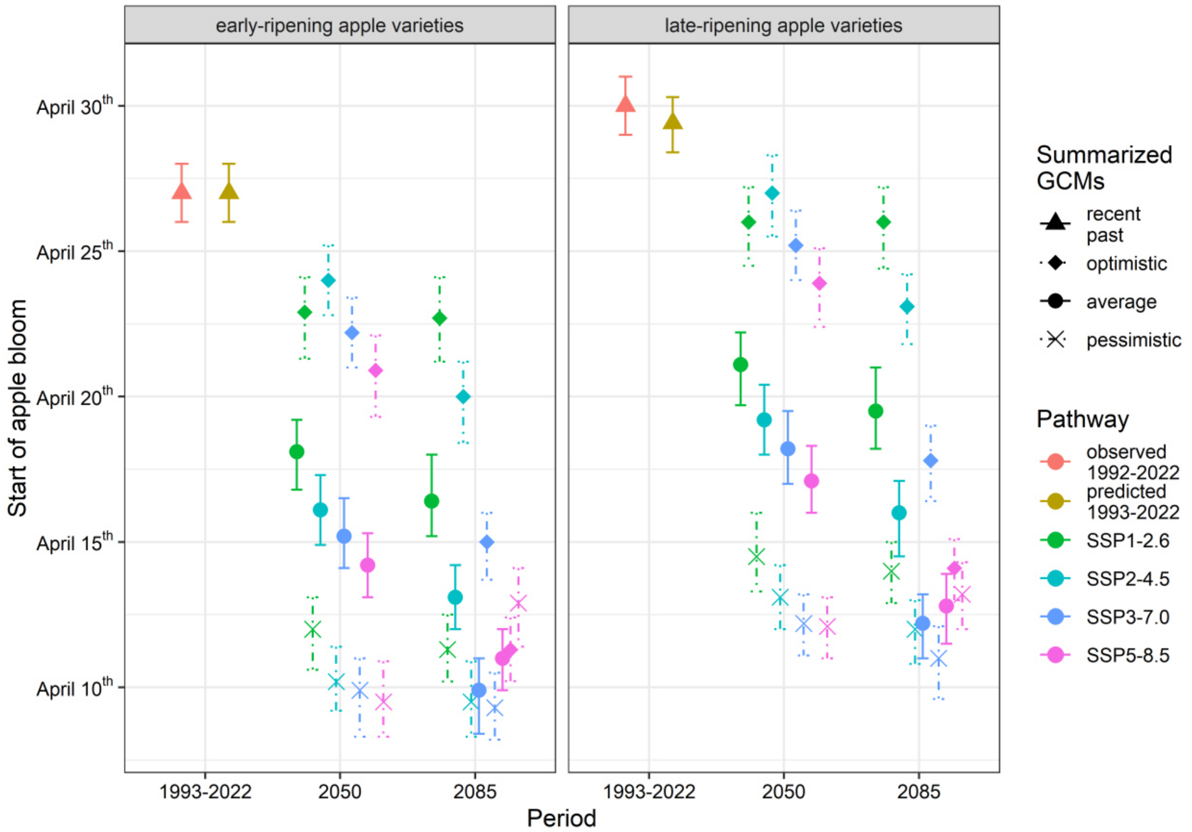


Figure 6: Median date for the start of bloom in the recent past (1993-2022, observed and predicted values) and in the future periods 2050 and 2085. Error bars show the 45% to 55%-quantile for each combination of SSP and summarized GCM. Solid error bars represent the historic data and the average model, while dot-dashed error bars represent the optimistic and pessimistic models.

3.3. Risk of frost damage in the future

3.3.1. Probability of years with frost damage >10%

Using the average model, the predicted probability of frost with more than 10% damage around 2050 is similar for all SSPs (Figure). All over Germany the predicted median probability of frost damage >10% ranges from 44% for SSP1-2.6 to 46% for SSP3-7.0 and SSP5-8.5. The forecast shows that frost damage is possible across the whole country. Even for the less affected coastal regions, we predicted a risk of at least 0.08% in SSP1-2.6 to 5.5% in SSP3-7.0 (Figure).

In comparison to the frost damage frequency in the recent past (1993-2022) (Figure), the probability of frost damage >10% will decrease in most regions (80%-83% of the raster cells covering Germany depending on the SSPs) by 2050. Mainly for the coastal regions in the North, parts of Saxony ("Ore Mountains") and Bavaria in the East as well as parts of the Alps in the South, the predicted frost damage probability is expected to increase (Figure). The median risk of frost damage >10% is expected to drop by 9 percentage points (pp) for SSP1-2.6, 7 pp for SSP2-4.5, and 8 pp for SSP3-7.0 and SSP5-8.5. The maximum predicted decrease is 41 pp (SSP1-2.6 and SSP3-7.0), but an increase in frost risk of up to 31 pp (SSP5-8.5) was found among the forecast outcomes.

The differences between the SSPs will be greater in 2085. The predicted probability of frost damage >10% slightly increases between 2050 and 2085 for SSP1-2.6 on about 86% of the country's surface area (Supporting Information 12). The median increase in the forecast was 2.6 pp. For the other SSPs, the forecast indicates a further decrease of the frost damage risk in apple growing from 2050to 2085 (Supporting Information 12). Comparing 1993-2022 with 2085, the predicted median frost damage risk decreases in 77% (SSP1-2.6) to 96% (SSP5-5.8) of the raster cells. The more severe the climate change scenarios are, the greater the predicted risk reduction. We predicted a median decrease of 6 pp under SSP1-2.6, 12 pp under SSP2-4.5, 18 pp under SSP3-7.0 and 29 pp under SSP5-8.5. At the same time, the percentage of area experiencing a decrease in frost damage risk increases with the severity of climate change scenarios, from 77% under SSP1-2.6 to 87% under SSP2-4.5, 90% under SSP3-7.0 and 96% under SSP5-8.5 (Figure). These differences are also reflected in the national median values for the risk of frost damage >10% in 2085, which are 47% for SSP1-2.6, 42% for SSP2-4.5, 37% for SSP3-7.0 and 25% for SSP5-8.5 (Figure).

3.3.2. Probability of years with frost damage >50%

Only some of the frost events in 2050 are expected to exceed the 50% damage threshold. The predicted median probability of frost damage >50% across Germany was 28% for SSP1-2.6 and 29% for SSP2-4.5, SSP3-7.0 and SSP5-8.5. There are large spatial differences for all SSPs, ranging from (almost) no risk of frost damage >50% (0-1.9% of the years) to frost damage >50% occurring essentially every year (99-100% of the years) (Figure 9).

In comparison to the frost damage frequency in the recent past (1993-2022) (Figure 5), the probability of frost damage >50% decreased in nearly half (44% of the raster cells for SSP2-4.5 to 49% of the raster cells for SSP1-2.6) of the country and increased in the other half (Figure 10). This results in only a slight decrease of 0.2 pp for SSP1-2.6 to 1.2 pp for SSP2-4.5. In the areas with increasing probability of frost damage, which are mainly in the North and East of the country, increases of up to 35 (SSP5-8.5) to 48 (SSP3-7.0) pp were observed among the model outcomes. The areas with decreasing risk of frost damage >50% are mainly located in western, southern and central Germany. For these regions, we predicted a decrease in frost damage risk by up to 23 (SSP3-7.0) to 25 (SSP1-2.6) pp (Figure 10).

As for the lower threshold value of >10%, a slight increase (median 2 pp) in the probability of frost damage >50% was observed for 2085 compared to 2050 for SSP1-2.6 in 88% of the raster cells. For the other SSPs, the frost damage risk decreases from 2050 to 2085 in 88%, 98% and 99% of the raster cells covering Germany for SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively (Supporting Information 12). Comparing 1993-2022 with 2085, the predicted frost damage risk decreased in 39% (SSP1-2.6) to 85% (SSP5-8.5) of the raster cells. The magnitude of the frost damage risk change depends on the SSP, leading to a median increase across Germany by 2 pp for SSP1-2.6 and a median decrease of 2 pp for SSP2-4.5, 6 pp for SSP3-7.0 and 13 pp for SSP5-8.5 (Figure 10). Thus, the median values for the probability of frost damage >50% for the year 2085 are 30% for SSP1-2.6, 26% for SSP2-4.5, 23% for SSP3-7.0 and 15% for SSP5-8.5 (Figure 9).

3.3.3. Frost damage risk in early- and late-ripening apple varieties

The spatial distribution of the risk of frost damage was found to be similar for early- and late-ripening apple varieties for both the >10% and the >50% damage thresholds. The effect of the different SSPs on the forecast results for 2050 and 2085 is also expected to be similar for apples of both ripening times (Supporting Information 4-11). When the current parameterizations of PhenoFlex (Supporting Information 2) for early- and late-ripening varieties were applied to the same future weather scenarios, the model predicted that the early-ripening varieties will flower earlier (Figure), but the late-ripening varieties will enter the sensitive '*green tip'* stage earlier in most cases. For example, comparing the PhenoFlex predictions for early-ripening varieties with the results for late-ripening varieties, at the phenology stations for the historical weather data, the '*green tip'* stage was predicted to occur 2 days earlier (based on the median; max.: 12 days earlier) in late-ripening apples.

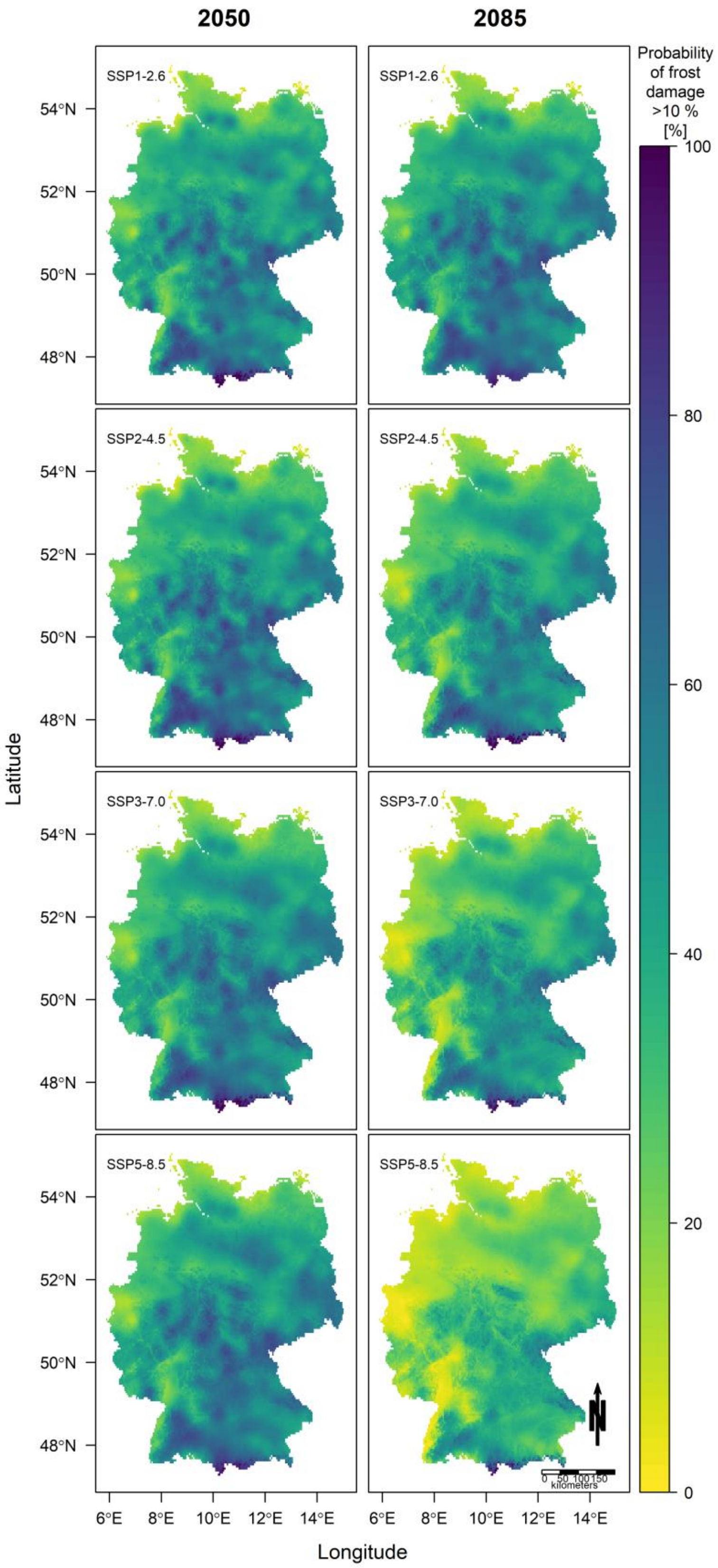


Figure 7: Probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits predicted for 2050 (left column) and 2085 (right column) for early-ripening apple varieties in Germany assuming different SSPs (rows) and the average model. Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

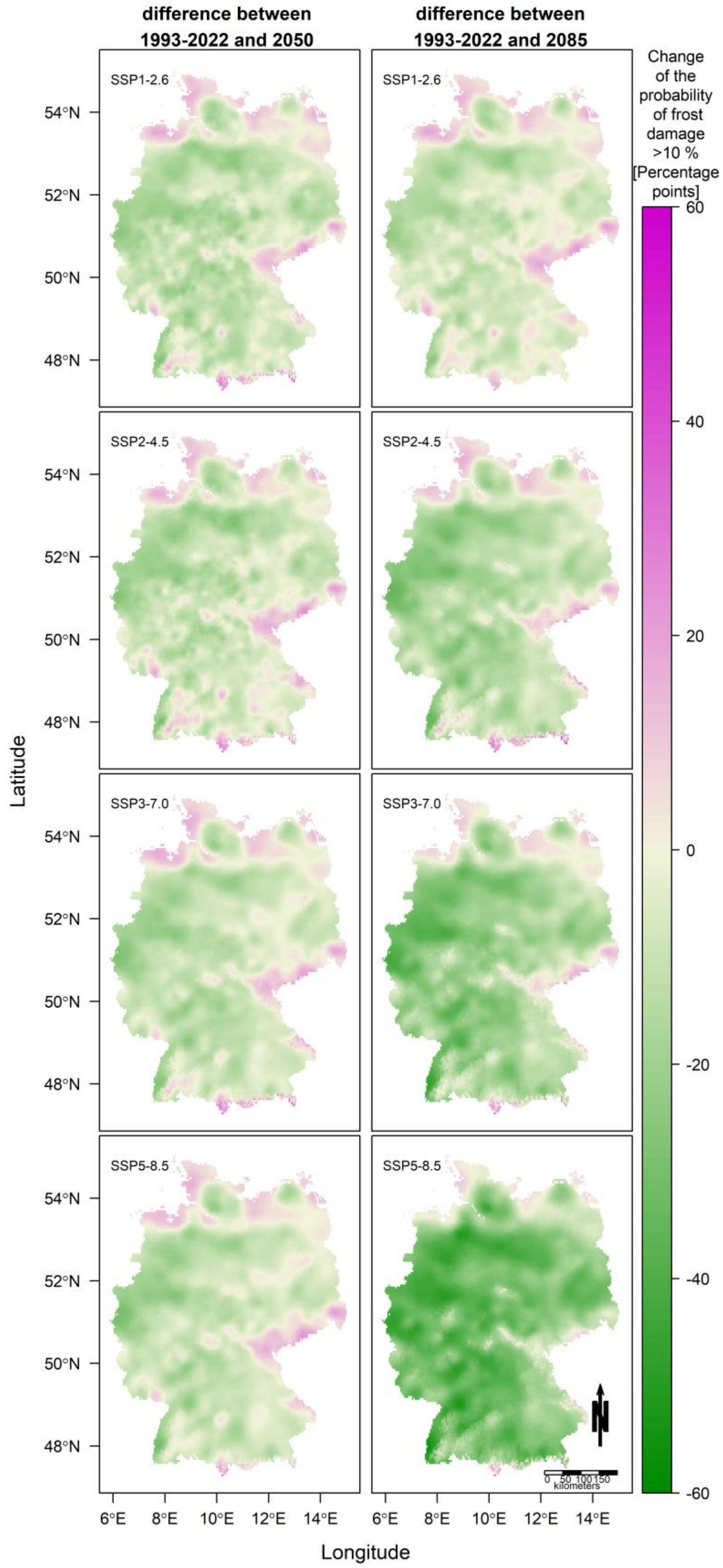


Figure 8: Change in the probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits between the recent past (1993-2022) and 2050 (left column) as well as between the recent past (1993-2022) and 2085 (right column) for early-ripening apple varieties in Germany, assuming different SSPs (rows) and the average model. Negative values (green) indicate a decreasing frost damage frequency and positive values (pink) indicate an increasing frost damage frequency. Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

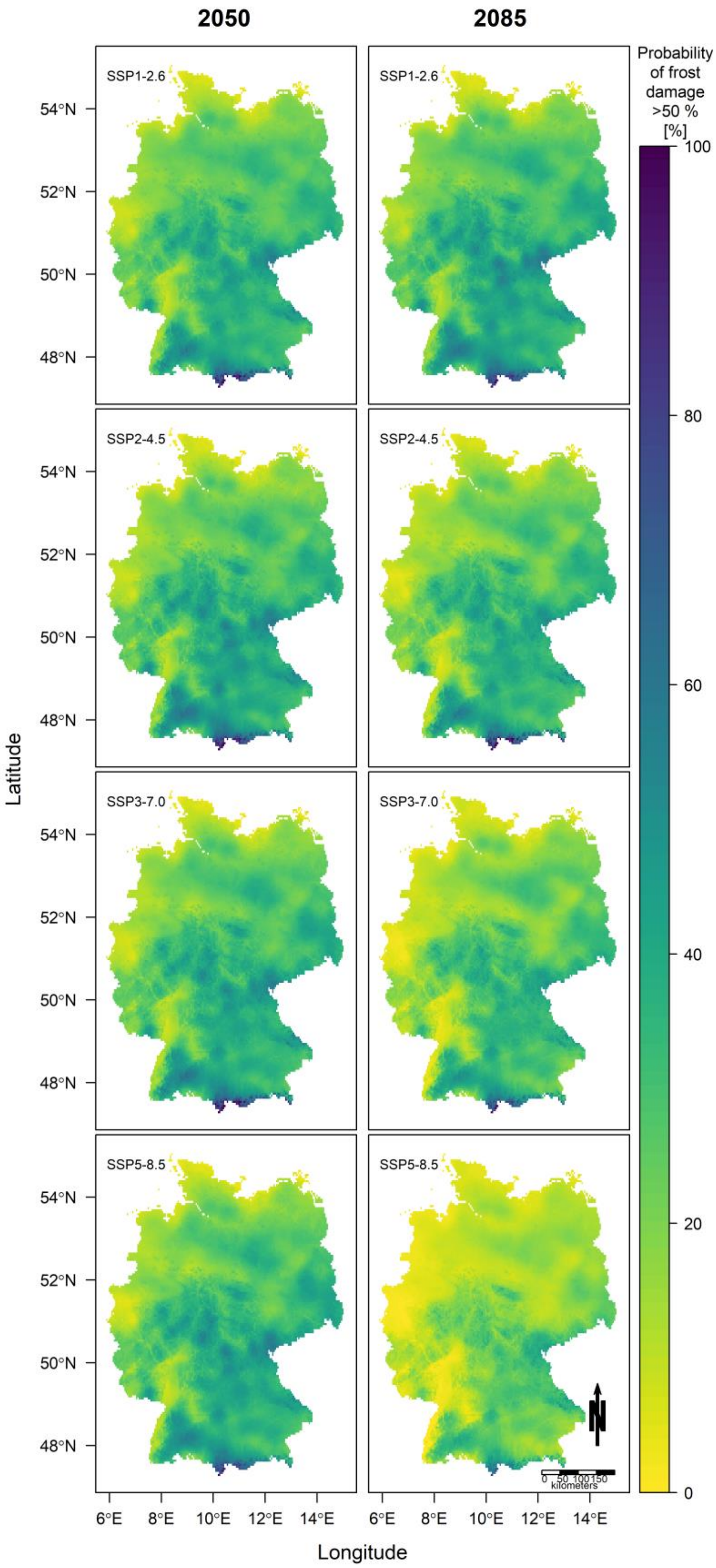


Figure 9: Probability of frost damage affecting more than 50% of the buds, flowers and young apple fruits predicted for 2050 (left column) and 2085 (right column) for early-ripening apple varieties in Germany assuming different SSPs (rows) and the average model. Maps are based on interpolated data for the probability of frost damage >50% and have a cell size of 0.05° (about 3.5x5.5 km)

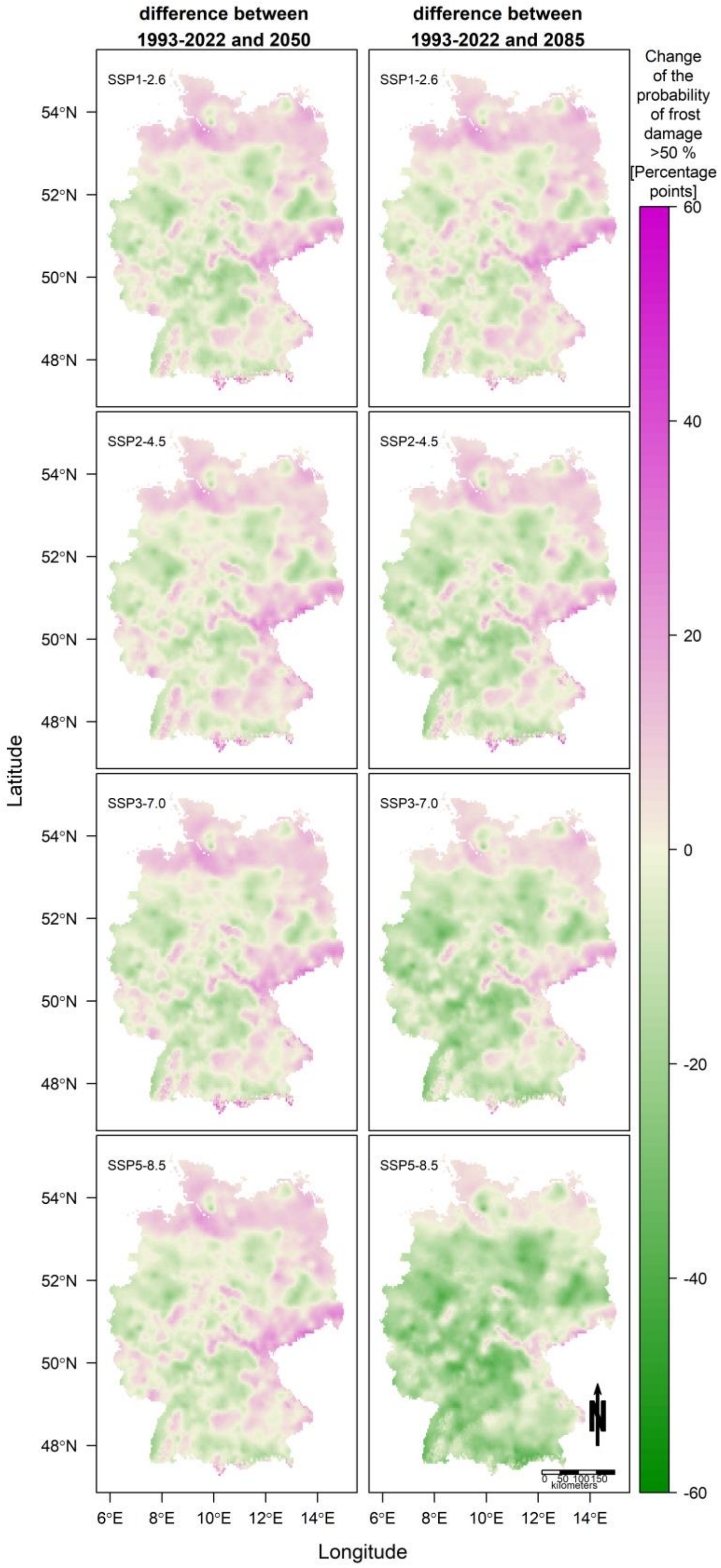


Figure 10: Change in the probability of frost damage affecting more than 50% of the buds, flowers and young apple fruits between the recent past (1993-2022) and 2050 (left column) as well as between the recent past (1993-2022) and 2085 (right column) for early-ripening apple varieties in Germany assuming different SSPs (rows) and the average model. Negative values (green) indicate a decreasing frost damage frequency and positive values (pink) indicate an increasing frost damage frequency. Maps are based on interpolated data for the probability of frost damage >50% and have a cell size of 0.05° (about 3.5x5.5 km)

This resulted in slightly greater frost risks (by 0.7 pp (SSP5-8.5, 2085, damage >50%) to 3.5 pp (SSP3-7.0, 2085, damage >10%), based on medians) in at least 73% of the raster cells covering Germany for the late-ripening varieties. Thus, for example the median probability of frost damage >10% across Germany in 2050 is predicted to be 44% (SSP1-2.6) to 46% (SSP3-7.9 and SSP5-8.5) for early- and 48% (SSP1-2.6 and SSP2-4.5) to 49% (SSP3-7.0 and SSP5-8.5) for late-ripening varieties (Figure , Supporting Information 8-11 "average").

3.3.4. Frost damage risk according to various climate models

In addition to the SSPs, which describe future socioeconomic developments, the predicted frost damage risk strongly depends on the GCM chosen for the prediction. The optimistic model represents the GCMs predicting a small temperature change and the pessimistic model the GCMs predicting a large temperature change. For all SSPs, the frost damage risk (for both the >10% and the >50% thresholds) is expected to be considerably higher under future weather conditions based on the optimistic model compared to the pessimistic model (Figure 11, Supporting Information 4-11).

The stronger the climate change described by the SSPs and the later the scenario year of the projection, the greater are the differences between the probability of frost damage under different models. In 2050, the median difference of frost damage >10% over all raster cells between the optimistic and the pessimistic model was 1 percentage point for SSP1-2.6, 5 pp for SSP2-4.5 and SSP3-70, and 8 pp for SSP5-8.5. Until 2085, the range of frost damage >10% risk increases to median differences of 9, 12, 18, and 24 pp between the optimistic and pessimistic models for SSPs SSP1-2.6, SSP2-4.5, SSP3-7.0 and SSP5-8.5, respectively (Figure 11, Supporting Information 4-11).

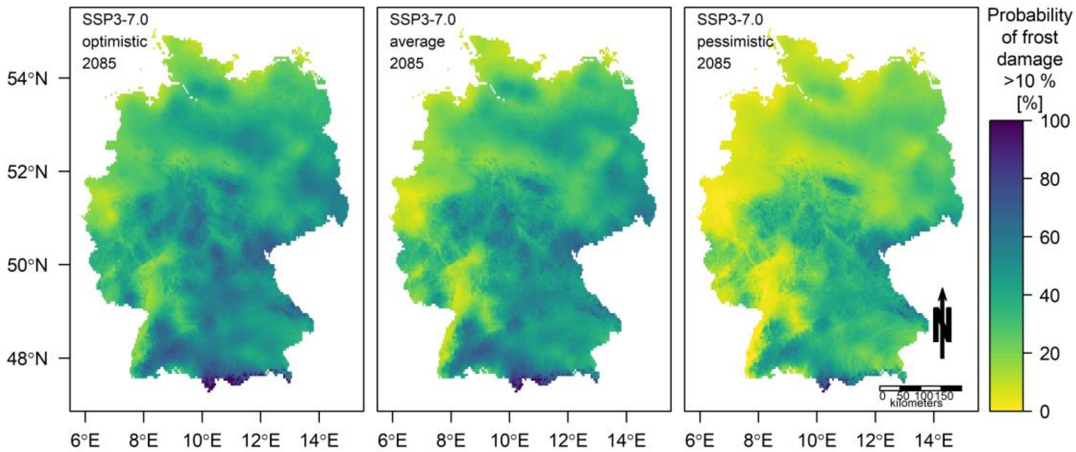


Figure 11: Probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits (early-ripening apple varieties) predicted for 2085 in Germany, under the pathway SSP3-7.0 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

4. Discussion

a Our study provides a comprehensive overview of the spatial distribution of late spring frost damage and its future development in German apple production. By using four SSPs and three summarized GCMs, we were able to represent the uncertainty regarding future climate development as fully as possible in the maps. The maps reveal that all important apple production regions (the "Altes Land" in the North, Saxony in the East, the Lake Constance region in the South and the "Rhineland" in the West) in Germany are faced with the risk of frost damage now and in the future (Figure 1, Figure , Figure ,

Figure , Figure). The maps not only provide information for the main apple growing areas, but also enable fruit growers, orchard meadow owners, hobby gardeners and other interested parties to inform themselves on the frost damage risk in their region under several future climate scenarios.

From a methodological point of view, the modeling workflow (**Fehler! Verweisquelle konnte nicht gefunden werden.**) presents substantial improvements over previous studies such as Bosdijk et al. (2024). First, we made projections and maps for four SSPs, covering a broad range of possible future climates. Second, to estimate the required heat accumulation for the transition between the phenological stages of apple buds, we referred to apple data by Chaves et al. (2017) instead of using cherry data by Anderson et al. (1986). Third, we improved the function to calculate the expected frost damage from a categorical classification to a sigmoidal function (Figure). These advances in phenology and frost damage modeling are of interest to the international fruit tree research community, as they may serve as a basis for further predictions of frost damage risk for other regions and tree species.

We predicted a future shift toward earlier bloom time of 8.9 (SSP1-2.6) to 12.8 (SSP5-8.5) days until 2050 for the average model (Figure). This is in line with several other studies that predicted a shift toward an earlier start of apple bloom (Hoffmann and Rath, 2013; Pfleiderer et al., 2019). Despite the clear trend toward earlier bloom in 2050, the predicted frost damage risk did not increase everywhere in the country (Figure & Figure).

We predicted a bloom delay in the 2085 period compared to the 2050 period for SSP5-8.5 and the pessimistic model, which may be due to reduced winter chill. Distinct analyses of chill and heat accumulation are also possible with PhenoFlex, but this was beyond the scope of this study. The probability of frost damage >10% is expected to decrease in most parts of the country until 2050, while the probability of strong frost damage (>50%) will probably decrease in some regions while increasing in others (Figure & Figure). Pfleiderer et al. (2019) also found spatial variation and differences between climate models underlying the predictions in the development of the number of frost days after blossom. Our results show that areas with decreasing and increasing frost risk can often lie close to each other.

Despite some major differences between SSPs, climate models and locations, it is evident that late frosts will continue to cause damage in apple cultivation in the years around 2050 and 2085 (Figure , Figure , Supporting Information 4-11). This confirms the findings of Pfleiderer et al. (2019) and Hoffmann and Rath (2013), who also predicted that, despite climate change, late frosts will continue to occur in important fruit-growing regions and Lower Saxony, respectively. Although the predicted probability of frost damage will increase to >50% in some regions by 2050, the results show that frost will not be a general exclusion criterion for apple production in Germany. However, as frost damage causes yield losses, which lead to economic challenges for fruit growers (Dalhaus et al., 2020), the challenge of finding suitable frost protection measures (Schmitz et al., 2025b) will remain relevant over the coming decades. Our maps provide comprehensive estimates of future frost risk, which may help farmers in their investment decisions. Taking future development into account is particularly important for perennial crops such as apples and other fruit trees, as fruit trees remain in place for many years and cannot be replaced annually. Early- and late-ripening varieties turned out to be almost indistinguishable in terms of first bloom dates (Figure) as well as the current and future frequency of frost damage. This finding implies that the ripening period is not a suitable marker of a cultivar’s susceptibility to frost.

The future risk of late frosts is also relevant from a political perspective. In recent years, subsidies have been paid out to support fruit growers after late spring frost events (e.g. BMEL, 2024). At the same time, there are repeated discussions about partially funding multi-risk insurance policies that cover late frosts. Knowledge about the future development of frost risk can help plan future support for fruit growers in a sustainable way.

The maps are produced with the help of a recent phenology modeling approach (Luedeling et al., 2021) and a large dataset of observations on the start of apple bloom. However, a few things should be considered while interpreting the results. The classification of the phenology dataset into early- and late-ripening apple varieties is not ideal for analyses focused on flowering time, as some late-ripening varieties - such as ‘Boskoop’ - typically bloom early or moderately early (Silbereisen et al., 1996). It is also worth noting that ‘Boskoop’ and ‘Klarapfel’ are not among the most important varieties in commercial apple production. While ‘Boskoop’ was grown on 719 ha (2% of the apple production area) in 2024 (Destatis, 2025), ‘Klarapfel’ is of no importance for the production of dessert apples. Nevertheless, due to its large size and even spatial coverage across Germany (Figure 1), the dataset was the best available for our analysis. Due to the mixture of different varieties in the analysis, it is not possible to base variety-specific statements about the future risk of frost damage on our analysis. However, since most apple varieties bloom during a similar period, our analysis of this diverse crowed-sourced phenology dataset still provides pointers about the general future trend in frost risk. For future phenology studies, it may be beneficial to analyze specific varieties, such as ‘Boskoop’ and ‘Weißer Klarapfel’, in greater detail. The PhenoFlex model focuses on the effect of temperature on phenology. Further effects on phenology such as the phenological feedback of prior frost damage (Wang et al., 2025) or legacy effects, e.g. due to drought (Liu et al., 2025), are not considered in the PhenoFlex modeling framework. However, as PhenoFlex predictions performed well in previous studies on apple phenology in Germany (Fernandez et al., 2022; Mojahid et al., 2025), we consider it a suitable component of our frost risk analysis.

Another important consideration is that the parameters of the PhenoFlex model are interdependent, which makes it difficult to directly compare fitted values across different parameterizations (Caspersen et al., 2024). This means that, for example, estimated chill and heat requirements of early- and late-ripening apple varieties are not directly comparable. These trade-offs do not undermine predictive skill, since compensating interactions between parameters ensure consistent phenology predictions. However, forecasts necessarily assume that these relationships remain valid under future climate conditions.

The RMAWGEN weather generator (Cordano and Eccel, 2016) does not specifically model extreme weather events, such as cold snaps or heatwaves, but generates daily minimum and maximum temperatures. Therefore, we repeated the weather generation 100 times for each scenario/model combination to cover a broad range of possible temperature scenarios. Nevertheless, rare extreme weather events may not have been covered by the synthetic temperatures.

Our estimate of frost damage is subject to certain simplifications. For example, using temperature measurements taken at a height of 2 m neglects the fact that apple trees also have branches at lower heights, which may be exposed to colder temperatures during radiation frost events. In addition, our analysis focused solely on whether a damaging frost event has occurred, without considering the duration of exposure to critical temperatures. As the critical temperatures reported by Ballard et al. (1981) were derived under different climatic conditions and for different varieties, their use in our analysis adds a potential error to our results. The training datasets were limited to weather stations and phenology reports from Germany, and they did not contain observations of apple bloom above an elevation of 925 m a.s.l. for late-ripening and 991 m a.s.l. for early-ripening apple varieties. Along with the complex terrain of some areas, such as the Alps, this may lead to estimation biases in some border regions and mountainous areas. However, as this applies only to a small part of the country, and apples are usually not grown at high altitudes, this is unlikely to affect our findings on national-scale trends.

Finally, the spatial resolution of our data (0.05°, 3.5x5.5 km) may mask small-scale structures in topography and microclimate that can influence the frost risk.

Most of these limitations and uncertainties, which lead, for example, to deviations between the estimated and actual phenological development, can result in overestimation or underestimation of frost damage. Some specific limitations, such as our inability to consider cold-air pools due to the low spatial resolution of the spatial grids, clearly lead to an underestimation of frost damage for the respective locations. All uncertainties and biases in our prediction may influence the actual damage to the trees. However, as these potential errors apply equally to all climate scenarios, time periods and apple varieties, we expect our analysis to deliver reliable estimates of future frost risk trends.

The SSPs represent alternative trajectories for future global society development. Combined with the RCPs, which represent the long-term global average of radiative forcing, they provide a framework for climate-related research (O'Neill et al., 2016). Although it is known that not all future CO_2 emission scenarios have the same probability (Ho et al., 2019), there is no clear consensus on which scenario is most likely.

To improve the quality of future frost risk studies as well as their practical relevance to fruit growers, it would be desirable to conduct targeted studies to determine the heat requirements of the apple varieties that dominate available phenology datasets. Additionally, updating the critical temperatures for frost damage for varieties that are currently dominating commercial apple production as well as for varieties covered by long-term phenology datasets would enhance the reliability of frost damage estimations. At the same time, it is important to continue collecting apple phenology data. Besides extending existing time series for varieties that have traditionally been monitored, data collection efforts should also cover modern cultivars to enable variety-specific analyses that are relevant for commercial orchards.

Although the probability of frost damage will decrease in many regions by 2085 in the more severe climate change scenarios (Figure , Figure , Supporting Information 4-11), climate change still poses a challenge for fruit growing. Besides changes in phenology and frost occurrence, further extreme weather events (Kron et al., 2019) and increasing pest and disease pressure (Skendžić et al., 2021) also threaten to compromise apple cultivation.

5. Conclusion

By applying a state-of-the-art phenology modeling approach in combination with an innovative method for estimating frost damage for the pre-bloom stages, we were able to create country-wide maps illustrating the spatial distribution of future frost damage risk. The maps cover a wide range of possible future climate conditions and provide guidance for fruit growers' operational decisions and for future policy-making. The results indicate that late spring frost will continue to pose a threat to apple buds, flowers and young fruits, even in a changing climate. The future extent and spatial distribution of frost damage risk strongly depends on the selected SSPs and climate models used for prediction.

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CRediT authorship contribution statement

C. Schmitz: Writing - original draft, Software, Investigation, Visualization, Conceptualization, Methodology; L. Caspersen: Writing - review & editing, Investigation, Methodology, Software, Conceptualization; J. Kopton: Writing - review & editing, Software, Visualization, Conceptualization, Methodology; K. Schiffers: Writing - review & editing, Supervision; Conceptualization, Methodology; E. Luedeling: Writing - review & editing, Methodology, Supervision

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Chapter 7: Topic related collaborations

During my studies, I collaborated with several researchers to develop a description for a common apple farm in the Rhineland, improve calibration training and estimate the carbon footprint of two training systems in apple production.

A collaboration with researchers from the Johann Heinrich von Thünen-Institut, Institut für Betriebswirtschaft resulted in the description of a hypothetical apple farm in the Rhineland using the typical farm approach. We organized an expert workshop with local advisors and fruit growers to gather relevant information and define the farm. The typical farm in the Rhineland was then compared with a typical farm in Styria (Austria). The results indicated that apple production with mature trees is profitable in the Rhineland, whereas in Styria, not all opportunity costs could be covered. We found that under the current economic conditions of apple farms, any further increase in costs could lead to economic difficulties.

Furthermore, I contributed to the improvement of an interactive online application used to train workshop participants in the estimating 90% confidence intervals. The app presents trivia questions to participants and records their estimates. In addition to answering these questions, the training includes a presentation of common cognitive biases and techniques to improve the accuracy of estimates. Since calibration training is a crucial step in the decision analysis workflow, the application supports the organization of expert workshops.

In addition, I was involved the development of a decision model to compare the training systems Spindle and Guyot for apple production, in terms of their Carbon footprint, labor demand, fuel demand and costs per kg apple. We conducted a participatory online workshop to involved fruit-growing experts in the modeling process and developed a probabilistic model. The results indicated with fairly high certainty, that Guyot orchards outperform spindle orchards across all observed parameters.

In the following chapter, I present the abstracts of these collaborations.

Rentabilität der Apfelproduktion im Rheinland und in der Steiermark – eine vergleichende Analyse

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Abstract

Rentabilität ist ein wichtiges Kriterium, um die Wettbewerbsfähigkeit auf Betriebsebene zu bewerten. In diesem Beitrag werden Kostenstrukturen und Erlöse von Apfelbetrieben in der Steiermark (Österreich) sowie im Rheinland (Deutschland) dargestellt. Die Datenerhebung wurde mit dem „typical farm approach“ durchgeführt. Typische Betriebe („typical farms“) sind Betriebsmodelle, die das typische Produktionssystem in einer gegebenen Region mit einem Preis-Mengen-Gerüst abbilden und auf Statistiken, Fokusgruppendiskussionen und Experteneinschätzungen basieren. Unterschiede zwischen den typischen Betrieben im Rheinland und in der Steiermark können u. a. in der Betriebsgröße und damit verbundenen Skaleneffekten, unterschiedlichen Vermarktungsstrukturen und bei den erzielten Preisen festgestellt werden. Die Vollkosten für den gesamten Betrieb können in beiden Regionen nicht gedeckt werden, wobei die Erlöse des typischen Betriebes im Rheinland einen größeren Anteil der Kosten decken als in der Steiermark.

Learn how to make accurate estimates: Calibration training with an interactive online application

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Abstract

Accurate estimation is a fundamental skill in decision science, essential for effective decision-making across various fields, including agriculture, environmental management, and policy development. To address the challenges of making reliable estimates, we developed an innovative online application designed for calibration training that helps students and professionals enhance their estimation skills using 90% confidence intervals. Our app provides a structured learning environment where users engage with binary and range questions, facilitating the development of their estimation capabilities. Participants are introduced to the concept of confidence intervals and trained to construct them effectively, fostering a deeper understanding of uncertainty in their estimates. We integrate insights into cognitive biases that often impede accurate estimation throughout the training. Participants learn to recognize and mitigate these biases—such as the Dunning-Kruger effect, anchoring bias, and confirmation bias—through practical examples and targeted exercises. By emphasizing the psychological factors influencing decision-making, we aim to cultivate a more nuanced understanding of how biases can skew judgment and lead to suboptimal decisions. Our app features a dual-interface design, catering to participants undergoing calibration and analysts facilitating the training. Participants (including experts, students, and stakeholders) are guided through questions that challenge their estimation skills, while analysts (lecturers, hosts, and administrators) can monitor progress and provide real-time feedback. This dual approach enhances the learning experience and promotes collaborative discussions around estimation techniques.

The carbon footprint of training system selection in apple production

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Abstract

Due to rising labor costs, varying production conditions within the European Union and stagnating revenues for growers, apple production in Germany's Rhineland-Palatinate is faced with an urgent need to reduce its production costs. A strong mechanization opportunity has arisen with the redesign of the classic spindle crown to mechanically cut and harvested narrow fruit walls. Such fruit walls are expected to simplify mechanical pruning and thinning, reduce pesticide use and drift, and improve the feasibility of applying sensors and robots within the production systems. From a sustainability perspective, clarity is needed on how this innovation might affect the carbon footprint of apple production. We therefore conducted a comprehensive carbon footprint analysis of different training and management systems that are commonly used in apple production. We assessed the classic spindle crown, mechanically pruned spindles and multi-leader fruit wall systems. We used a decision analysis approach to build a multifunctional model of the observed systems, using literature and expert knowledge to gather information on all influencing variables and factors. From this conceptual model, we derived information on all materials and resources that are used for orchard management in two scenarios. We calculated the carbon footprint for all important model factors, based on information from a life cycle inventory database. Combining these methods enabled us to assess the consequences of changing training systems in apple production and may have wider application to other horticultural management decisions.

Conclusion

In times of various challenges for the regional tree fruit production and declining capacities in fruit growing advice, there is a strong need for scientific work on practically relevant topics. The main goal of this thesis was to address relevant questions in fruit production, primarily in Germany and to provide practical forecasting tools and risk prediction models by applying innovative scientific modeling approaches.

This thesis focuses on the modelling of temperate fruit tree fruit systems, with a particular emphasis on apple production. Apple served as the primary model crop and was central to investigations of historical (Chapter 3) and future risk of late spring frosts (Chapter 6), the economic feasibility of frost protection measures (Chapter 5), and the development of ProbApple, a forecasting tool for yield and quality (Chapter 2). In addition to apple, apricot was included in the initial development of a decision support model for frost protection (Chapter 4). Across all studies, the overarching objective was to support high yield and fruit quality in temperate orchard systems. The ProbApple model presented in Chapter 2 characterizes the effects of various environmental and management factors on apple yield and quality throughout the growing season. Among these, the occurrence of late spring frosts emerged as a critical limiting factor and was analyzed in detail in Chapters 3 to 6. Chapters 4 and 5 describe the development of a probabilistic decision support system for frost protection. Chapter 4 focuses on a simplified model with limited intervention options applicable to mature orchards, whereas Chapter 5 expands this framework to evaluate a broader range of strategies across the full orchard lifecycle. Finally, Chapter 6 builds upon the findings of Chapter 3. The analysis of historical late spring frost frequency in Chapter 3 serves as the foundation for the map-based approach, which is also applied in the future frost risk projections in Chapter 6.

From a methodological perspective, Chapters 2, 4, and 5 share the use of probabilistic modelling within a decision analysis framework, although ProbApple is not a decision model per se. In contrast, Chapters 3 and 6 utilize Kriging interpolation to generate spatially explicit, countrywide frost risk maps. Notably, Chapter 6 also integrates the process-based phenological model PhenoFlex to project future bloom dates under several climate scenarios.

The findings of the studies offer examples of digital supporting systems in fruit production, while also disclosing some challenges for the transfer from science to practical fruit growing.

The individual models address different planning horizons. ProbApple is primarily suited for short-term planning during the growing season — for example, in organizing harvest operations — whereas the frost protection investment model supports long-term planning over the full lifespan of an orchard, which typically spans around 18 years for apple production.

The ProbApple tool, developed as part of this work, enables fruit growers to forecast apple yield at harvest using parameters that can be easily estimated during routine orchard tasks. The model and its results emphasize that apple yield and high-quality yield are influenced by a variety of risks throughout the fruit development and ripening process. Given the uncertainty surrounding both the occurrence and potential severity of risks, probabilistic modeling was an appropriate framework to provide forecasts that transparently reflect all uncertainties in the model outcome. ProbApple illustrates how the decision analysis workflow and coding approach can be adapted to create probabilistic forecasts even in the absence of a concrete decision context. However, the output distributions of ProbApple often span a wide range, which may not align with the expectations of the fruit growers. It is therefore essential to clearly explain the structure and interpretation of the model output to users to ensure that the tool can be effectively applied in short- and long-term planning.

Fruit growers are becoming increasingly aware of ongoing climate change. A noticeable trend toward earlier fruit tree blossom, combined with several late spring frost events in recent years, has raised concerns about late frosts, which can significantly impact fruit yield and quality—particularly early in the vegetation period. As a result, there is growing interest in local frost risk and implementing effective frost protection strategies. To provide evidence-based information on both past and future frost risks, my co-authors and I analyzed historical frost occurrences during apple bloom from 1993 to 2022 and projected future risks for 2050 and 2085 under various climate scenarios. Additionally, we evaluated the economic viability of different active frost protection measures in apple and apricot production.

The results of the spring frost studies confirm that late spring frost is a relevant problem in German apple production and remains a persistent threat in future. As the frost risk is a highly important variable in the projection of the economic viability and it is expected that spending up to 1626 €/ha (in the evaluation of overhead irrigation) in gaining further knowledge on the frost risk would be worthwhile, the maps for the future frost risk enable to improve the model with region-specific inputs. With the current estimates, the simulations for Rhineland and Lake Constance region indicate that while frost protection improves yields, it often fails to offset the associated costs. The results from the scenario without frost protection also indicate that apple production is often not economically viable. However, the model's estimates were produced during a period of significantly elevated energy prices, largely driven by the Russia-Ukraine conflict, with the expectation that these costs would remain high or rise further. Since then, the cost situation has somewhat stabilized, although ongoing global political uncertainties continue to pose potential risks to the agricultural and horticultural sectors.

The insights into frost risk and frost protection are of importance not only to fruit growers but also to policymakers. In recent years, there has been a general political willingness to assist fruit producers affected by frost events, as demonstrated by the emergency subsidies granted in 2017 and 2024. By incorporating knowledge of future frost risks and the economic implications of applying various active frost protection strategies, more targeted and sustainable support schemes could be designed. This approach would help minimize the substantial administrative burden and uncertainty associated with reactive emergency aid.

Decision analysis aims for a holistic view on the modeled system, aiming to include all relevant factors that matter for a decision or modeling question. For topics like fruit quality and yield, which are influenced by a wide array of natural factors and management measures, determining the appropriate level of detail in modeling was sometimes challenging. As a result, certain compromises, such as omitting the explicit modeling of frost-related effects on alternate bearing in the frost protection decision framework were necessary. However, the simplification that I made were covered by the variability of the superior factor, which is the annual yield of mature trees in this case. The discussions held with the experts during workshops and after presentations helped to properly developing the structure of the decision model. This meant that we were able to incorporate knowledge from the practical world of fruit growing into the model.

My contributions to enhancing the calibration training application have aimed to streamline the technical aspects of the training process, thereby enabling participants to focus more effectively on refining their estimation skills. Despite these improvements, it became evident that actively encouraging experts to engage in such training is crucial. Experts often exhibit a preference for activities directly related to their domain, such as decision framing or the assessment of costs, risks, and benefits, over participation in calibration exercises.

The models developed in this thesis provide a solid foundation for future research and practical applications. My co-authors and I made our model code publicly available, enabling other modelers to use, adapt or update the models. The frost protection decision model can be readily updated by modifying the input tables should future cost structures deviate from current estimates. With additional effort, both the frost protection model, but also ProbApple can be extended to other tree fruit species. ProbApple requires input estimates such as the number of apples per tree or the diameter of the fruit, which so far have to be estimated by the model users. Such parameters to be also determined automatically through the evaluation of camera or sensor data. Although it is not yet standard practice for tractors or other fruit-growing equipment to be equipped with such technologies, ongoing progress in digitalization suggests strong potential for integrating automated fruit detection methods with ProbApple. This integration could significantly reduce the effort required by farmers to use the model, enhancing its practicality and adoption. Beyond frost risk protection and yield estimation, many other farm-level investment and planning decisions can benefit from similar probabilistic modeling approaches. The knowledge that has been consolidated in the form of model components, parameter values, and source code from existing models provides a valuable basis for the extension and development of new probabilistic models in orchard planning.

Developing similar frost risk maps for additional fruit species that flower earlier than apples, such as apricots, could enhance our understanding of climate change impacts on fruit production and provide valuable decision support for selecting tree species for new orchards.

Overall, the findings of this thesis confirm that fruit growers in Germany face a challenging economic environment. Investment decisions should be taken carefully, as illustrated by the case of frost protection: while such measures are highly effective in safeguarding yields, they were found to be economically unviable in many instances. The long-term frost risk projections, which extend over several decades, offer valuable insights for strategic decisions, such as determining the future orientation of a fruit-growing enterprise. In general, the results demonstrate that the forecasting tools presented in this thesis provide relevant information for several groups of stakeholders in the area of fruit production, including fruit growers, advisors, policymakers, and scientists.

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In addition to the current team, I would also like to thank some former HortiBonn members. Michael—thank you for your enthusiasm and for generously sharing your vast knowledge and experience. I'm also thankful to Shyam and to the technical staff—especially Ira, Gertrudis, and Birgit—for making the summer of 2020, when I wrote my master's thesis, a great experience despite COVID. Without you, I would have never decided to start a PhD.

Thanks to Hildegard and Anika from the Thünen Institute, as well as Zoe and Lars, for the collaboration on describing a typical fruit growing farm in Rhineland. I'm also grateful to Nyanghura, Philipo, Lisa, and Cory for the opportunity to conduct calibration training during two expert workshops in Tanzania.

Again, I'd like to thank all the fruit-growing experts who contributed to the workshops and generously gave their time to participate in discussions, calibration training, and the estimation of input values.

I am grateful for the funding of the Experimentierfeld Südwest project by BMEL [grant numbers 28DE111B18 and 28DE111B22], which enabled my research. Many thanks to the Dienstleistungszentrum Ländlicher Raum Rheinpfalz for allowing me to be part of this project.

A big thank you also goes to the EF-Südwest project coordination team, led by Daniel. Special thanks to Elisa and Jona for their work behind the scenes in structuring the project, and to Manuela for handling all financial matters in our sub-project.

Finally, I extend my heartfelt thanks to my friends— especially Kathi, Meret, Lilith, Theresa, Rebecca, and Simone—as well as my colleagues and the children from the gymnastics club, and my choir friends, for their encouragement and welcome distractions during stressful times.

Last but not least, I would like to thank my cat, Luna, for her pleasant presence and companionship, and for the fun she brought to some of the online meetings.

Annex

Supplementary Material for Chapter 2

Supporting Information

ProbApple – A probabilistic model to forecast apple yield and quality.

Christine Schmitz[1,2], Lars Zimmermann[1,2], Katja Schiffers[2], Martin Balmer[1], Eike Luedeling[2]

[1]Dienstleistungszentrum Ländlicher Raum Rheinpfalz, Rheinbach, Germany;

[2]INRES – Horticultural Sciences, University of Bonn, Germany

Supporting information 1: Model code and Input files

The R Code for ProbApple and the visualization of the simulation results is available on GitHub in the following repository: https://github.com/ChristineSchmitz/ProbApple (Schmitz et al., 2024).

The functions of the ProbApple model are shown in ProbApple_Code.R. Simulations_with_ProbApple.R loads the ProbApple model and the required inputs to run a Monte Carlo simulation. The model requires three input data files: i) a main file which contains all estimates that are related to growing region and apple variety (apple_quality_input_Gala.csv), ii) a file with orchard- and year-specific inputs (apple_estimation_Gala.csv, Table 2 in the main text), and iii) a file that defines which management measures are conducted in the orchard (Management_inputs.csv, Management_inputs_without_hailnet.csv, Table 1 in the main text).

Plotting_ProbApple_simulation_results.R visualizes the simulation results generated with ProbApple.

Supporting information 2: Model results

The simulation results for the case study on ‘Gala’ apple in the Rhineland with the scenarios “with anti-hail netting” and “without anti-hail netting” are stored in the same repository: https://github.com/ChristineSchmitz/ProbApple.

The simulation results for both scenarios at all four forecasting time points (at full bloom, before fruit thinning, after June drop and 4 weeks before the estimated harvest date) are stored in the Folder MC_results. The results are provided as RDS (containing model returns and values drawn from the input distributions) and csv files (only model returns).

Supporting information 3: Instructions for input value estimation

The inputs values can be adjusted for different scenarios by changing the values (lower and upper) or the distribution type in the input table.

The distribution types used in the model are:

- *norm*: normal distribution
- *posnorm*: positive normal distribution
- *tnorm_0_1*: truncated normal distribution (only takes values between 0 and 1)
- *const*: constant value – no distribution

Generally, the value for *lower* must be smaller than the value for *upper*. The only exception is the distribution type *const*, where *lower* and *upper* must have the same value.

Further distribution types can be found in the reference manual of the decisionSupport package: https://cran.r-project.org/web/packages/decisionSupport/decisionSupport.pdf

The values should be provided in the form of 90% confidence intervals to express the uncertainty regarding the input, i.e. *lower* is the 5%-quantile and *upper* the 95%-quantile.

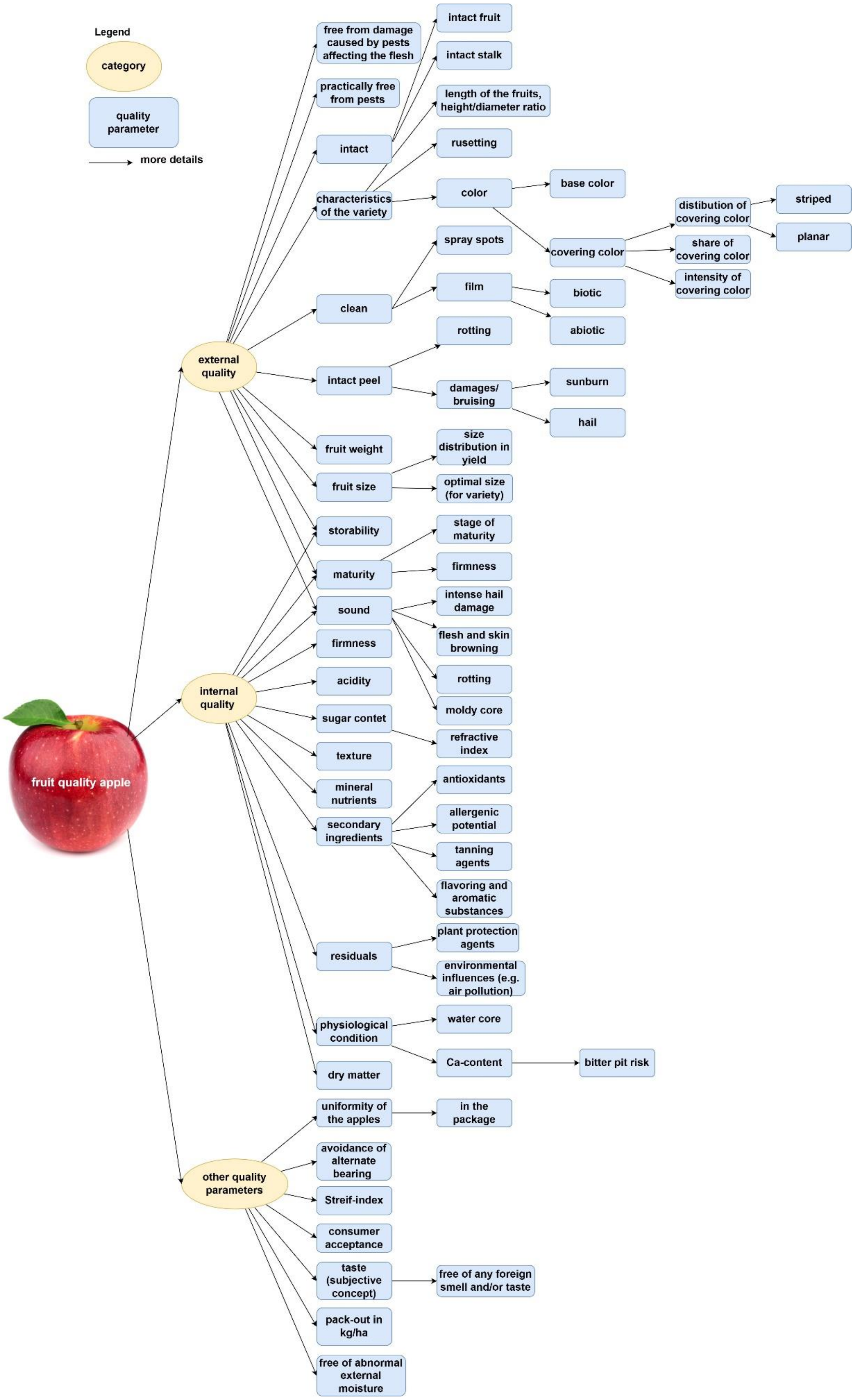
The column *variable* should not be changed, because the model needs the variable name to refer to the appropriate input.

In most cases, the combination of variable, unit and description should provide enough information to understand the meaning of the variable. It may be helpful to know the forecasting time points:

- tp1: at full bloom
- tp2: before fruit thinning
- tp3: after June drop
- tp4: 4 weeks before the estimated harvest date.

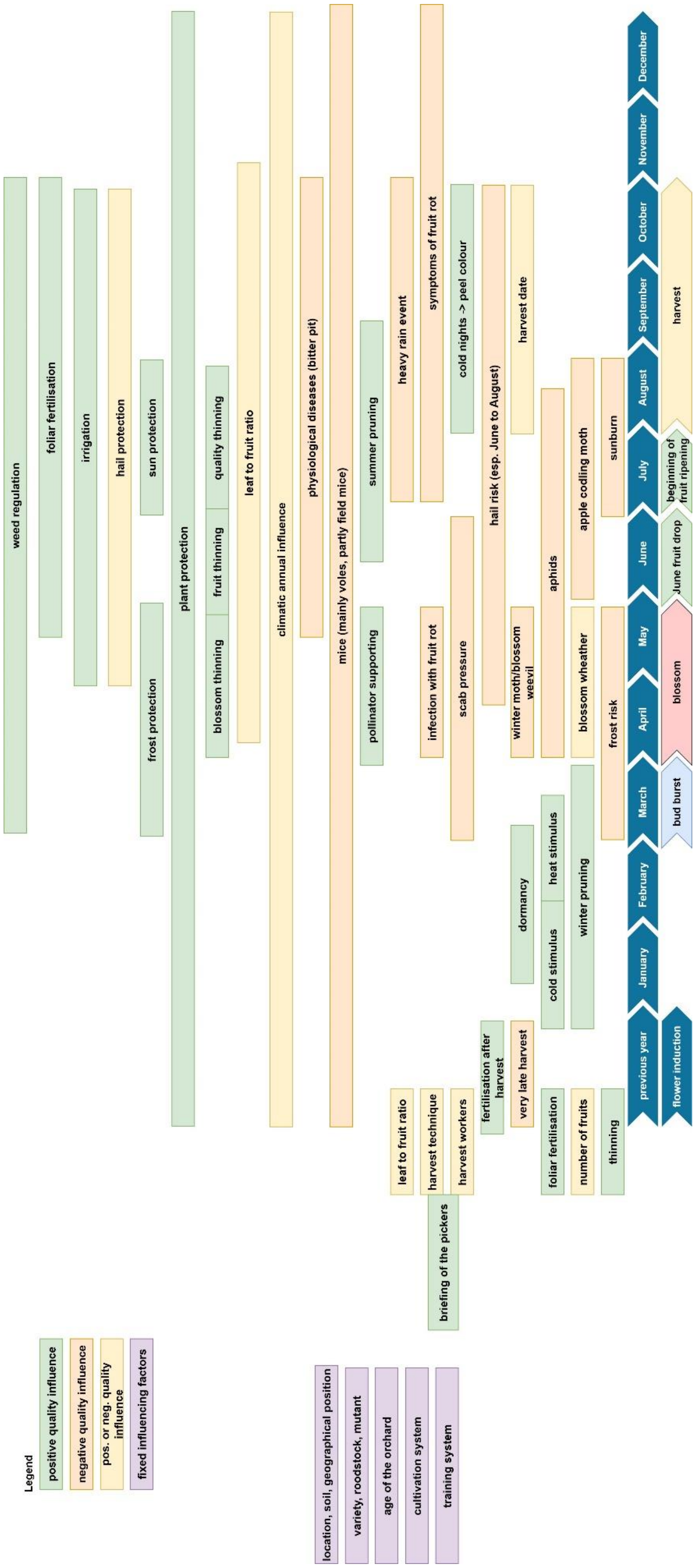
Most risks use two estimates to describe the situation: the risk and the damage. Risk is defined as the probability that at least some damage occurs within the time period (could be imagined as the answer to the question “In how many of 100 years does the respective risk event cause damage?”). Damage is the proportion of apples that get damaged, assuming that the risk event takes place. It can be quite realistic that the risk is high but the damage is low, or vice versa.

Supporting information 4: Workshop results – quality parameters



Supporting Information 4: Quality parameters of apple, as mentioned during the workshop or the marketing standards for apples in the EU (European Commission, 2004)

Supporting information 5: Workshop results – influences on fruit quality



Supporting Information 5: Quality influences over the year, listed by fruit growing experts in a participatory online workshop.

References

European Commission, 2004. Commission Regulation (EC) No 85/2004 of 15 January 2004 laying down the marketing standard for apples.

Schmitz, C., Zimmermann, L., Schiffers, K., Balmer, M., Luedeling, E., 2024. Supporting Information: ProbApple – A probabilistic model to forecast apple yield and quality. Zenodo. https://doi.org/10.5281/ZENODO.14202191

Supplementary Material for Chapter 5

Supporting Information

Model-based decision support for the choice of active spring frost protection measures in apple production

Christine Schmitz[1,2], Lars Zimmermann[1,2], Katja Schiffers[2], Cory Whitney[2], Martin Balmer[1], Eike Luedeling[2]

[1]Dienstleistungszentrum Ländlicher Raum Rheinpfalz, Rheinbach, Germany;

[2]INRES – Horticultural Sciences, University of Bonn, Germany

Supporting information 1: Model code and input files

The R Code for the decision model and all other code needed to use the model is available on GitHub in the following repository: https://github.com/ChristineSchmitz/Supporting_Information_DA_Frost_Protection. The repository is citable via a Zenodo DOI (https://doi.org/10.5281/zenodo.11473204).

The input values used in our simulation are stored in three files:

1) General inputs (https://github.com/ChristineSchmitz/Supporting_Information_DA_Frost_Protection/blob/main/Frost_protection_input_apple_supplementary.csv) contains all inputs valid for both case study regions (Rhineland and Lake Constance)
2) Region-specific inputs (https://github.com/ChristineSchmitz/Supporting_Information_DA_Frost_Protection/blob/main/frost_scenario_supplementary.csv) contains the input values that differ between the Rhineland and the Lake Constance region
3) Additional information (https://github.com/ChristineSchmitz/Supporting_Information_DA_Frost_Protection/blob/main/Information_input_apple_supplementary.csv) contains additional information needed to calculate the investment costs

Supporting information 2: Model results

The Monte Carlo results are stored on Zenodo in the repository *Model results: Model-based decision support for the choice of active spring frost protection measures in apple production* (https://doi.org/10.5281/zenodo.11470867).

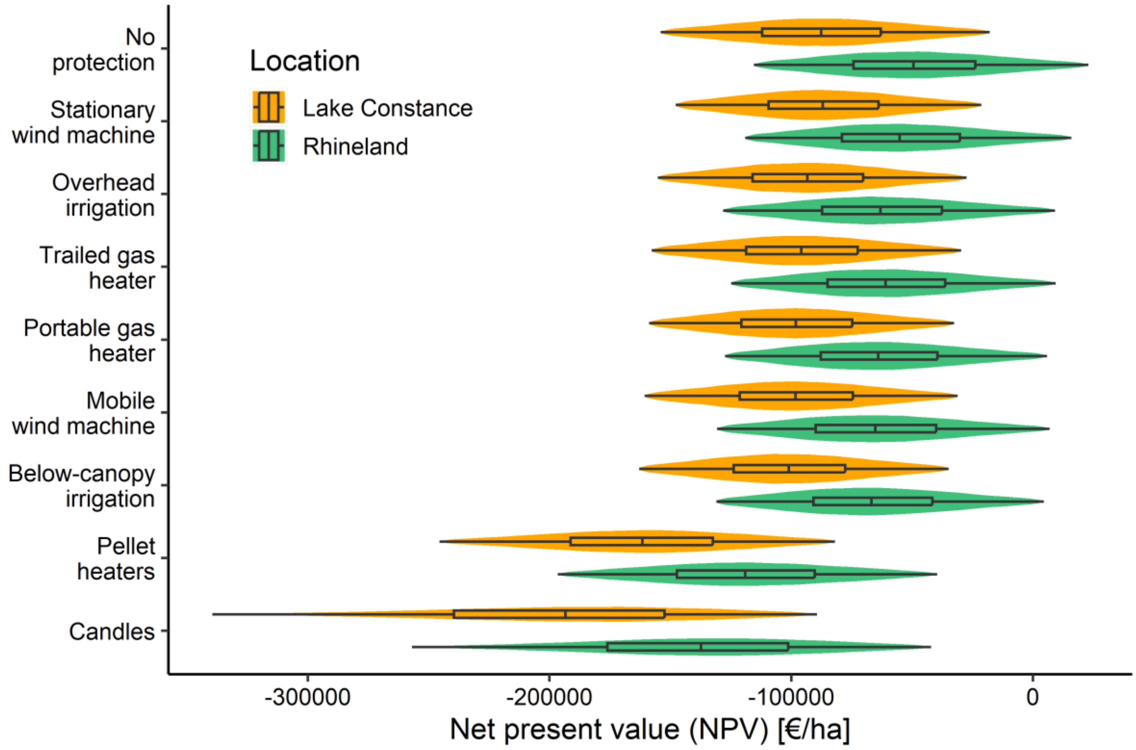
The RDS files can be used to open the data in R and they can be handled by the functions we used for Post-hoc analysis and plotting. Additionally, we provide the results as csv files.

The results of the Expected Value of Perfect Information (EVPI) analysis are stored on GitHub in the files evpi_Rhineland.csv (https://github.com/ChristineSchmitz/Supporting_Information_DA_Frost_Protection/blob/main/evpi_Rhineland.csv) for the Rhineland and evpi_LakeConstance.csv (https://github.com/ChristineSchmitz/Supporting_Information_DA_Frost_Protection/blob/main/evpi_LakeConstance.csv) for the Lake Constance region

Supporting information 3: Variable Importance in Projection (VIP)

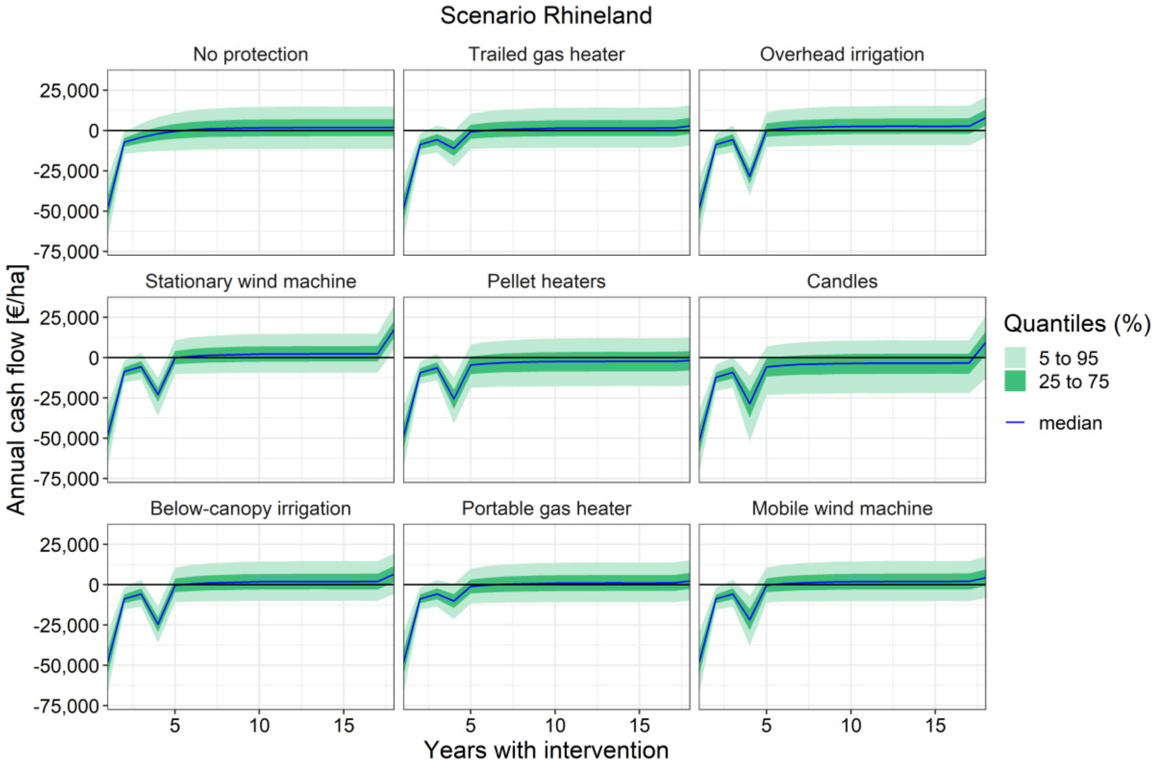
Supporting information 3: Variable Importance in the Projection scores of a Partial Least Squares regression model of several decision options of implementing frost protection measures in apple orchards compared to no protection. The left column displays results for the Rhineland and the right column for the Lake Constance region. Vertical black lines indicate the VIP=1 variable importance threshold. Red bars indicate a negative correlation with the NPV of the decision and blue bars indicate a positive correlation.

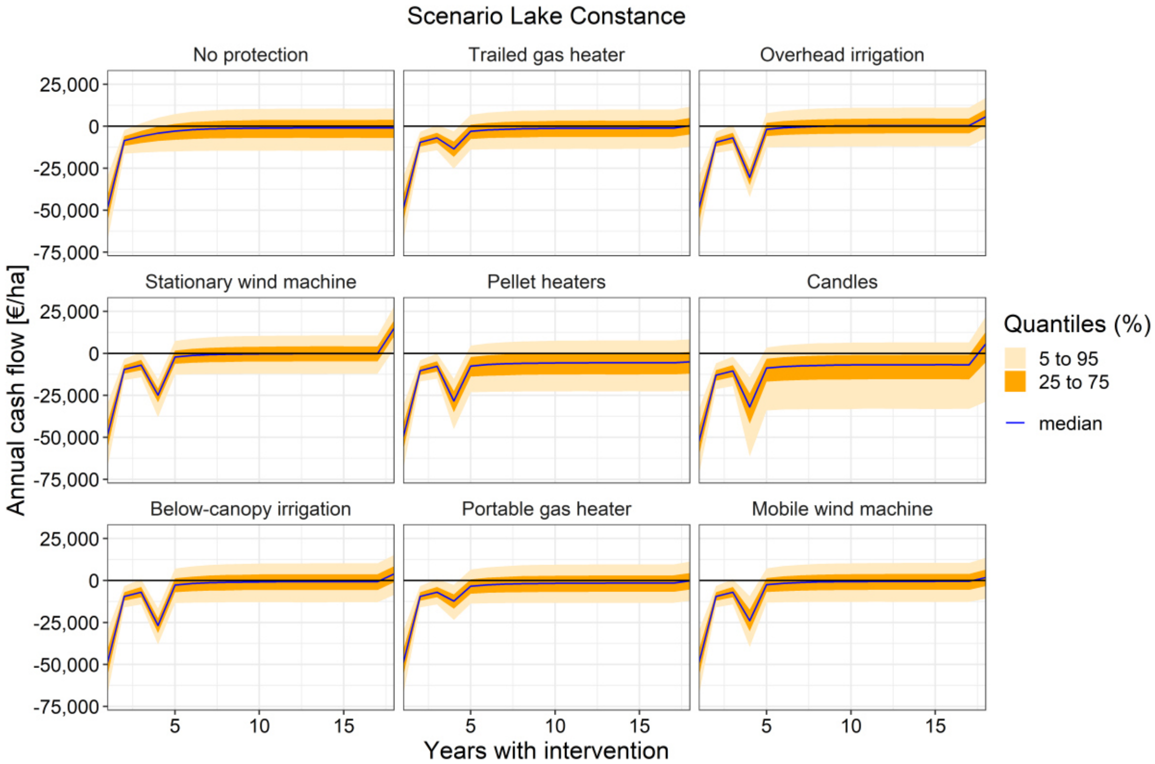
Supporting information 4: NPV



Supporting information 4: Net Present Value [€/ha] of several decision options of implementing frost protection measures in apple orchards. Box- and violin plots show the values between the 5 and 95 percent quantiles of 100,000 Monte Carlo simulation runs of the decision model. Green boxes show the results for the Rhineland and orange boxes for the Lake Constance region.

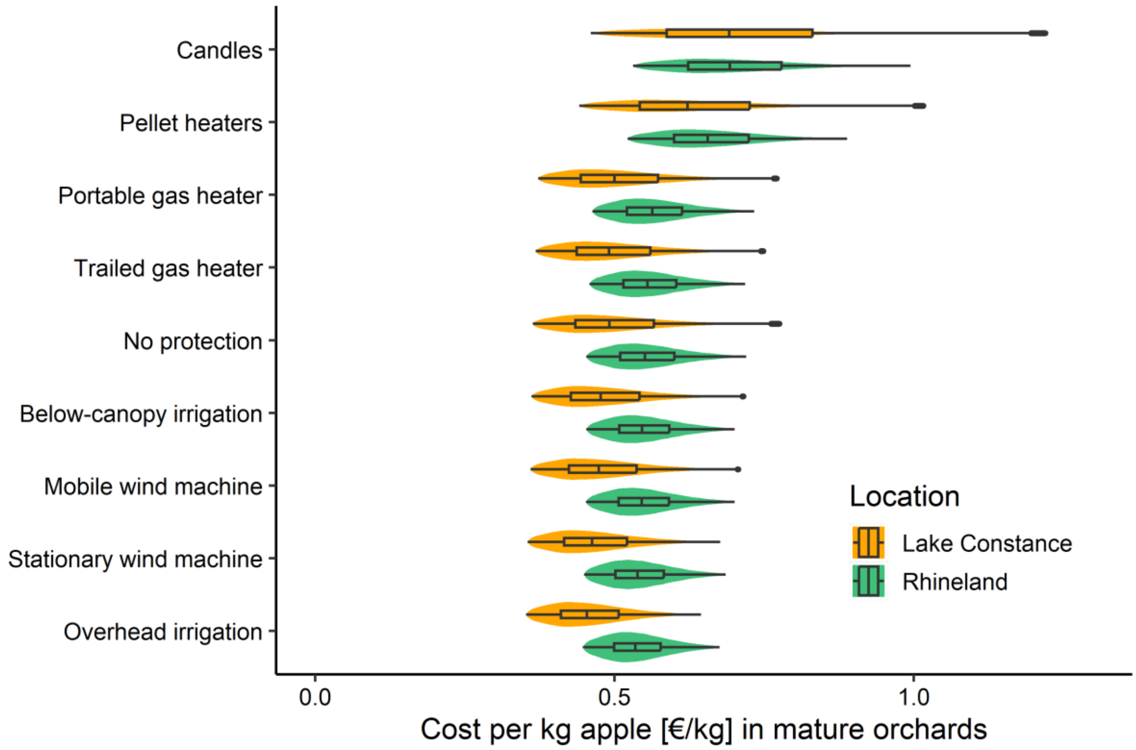
Supporting information 5: Cash flow plots





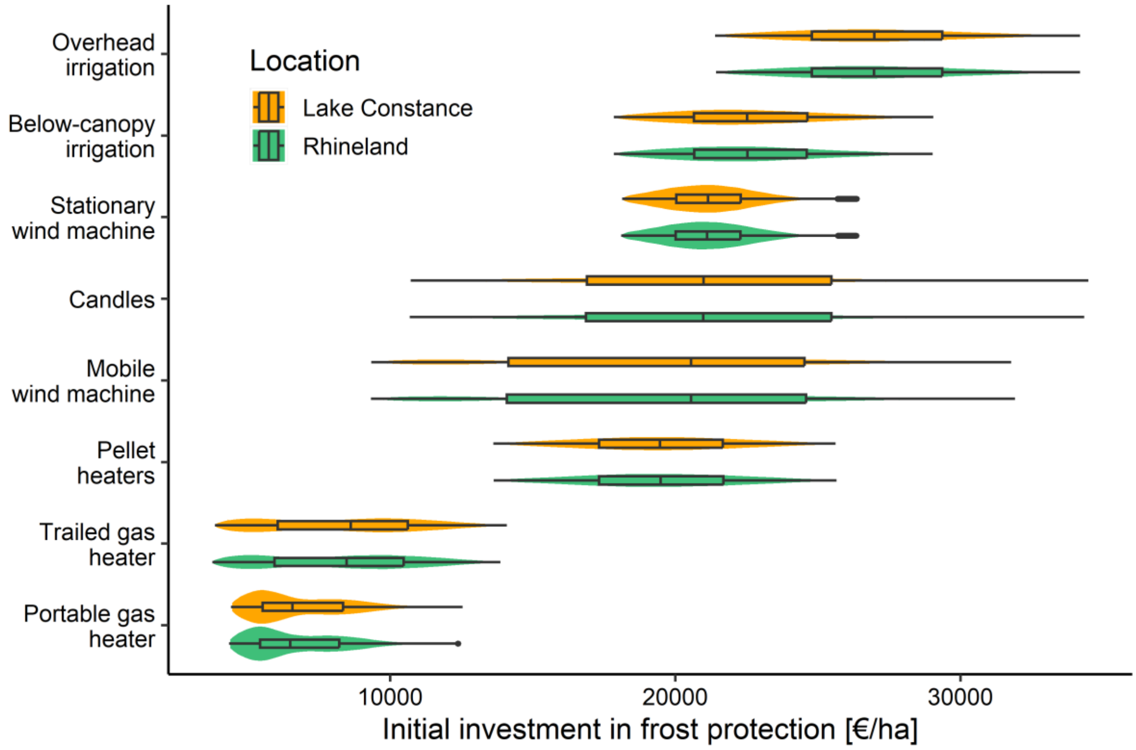
Supporting information 5: Probability distributions of projected annual cash flow (Euros per ha) over 18 years of apple orchard lifetime for several decision options of implementing frost protection measures in apple orchards. The upper plot displays the simulation results for the Rhineland and the bottom plot for the Lake Constance region. The probability distributions were generated with 100,000 Monte Carlo simulation runs of the decision model.

Supporting information 6: Cost per kg apple (mature trees)



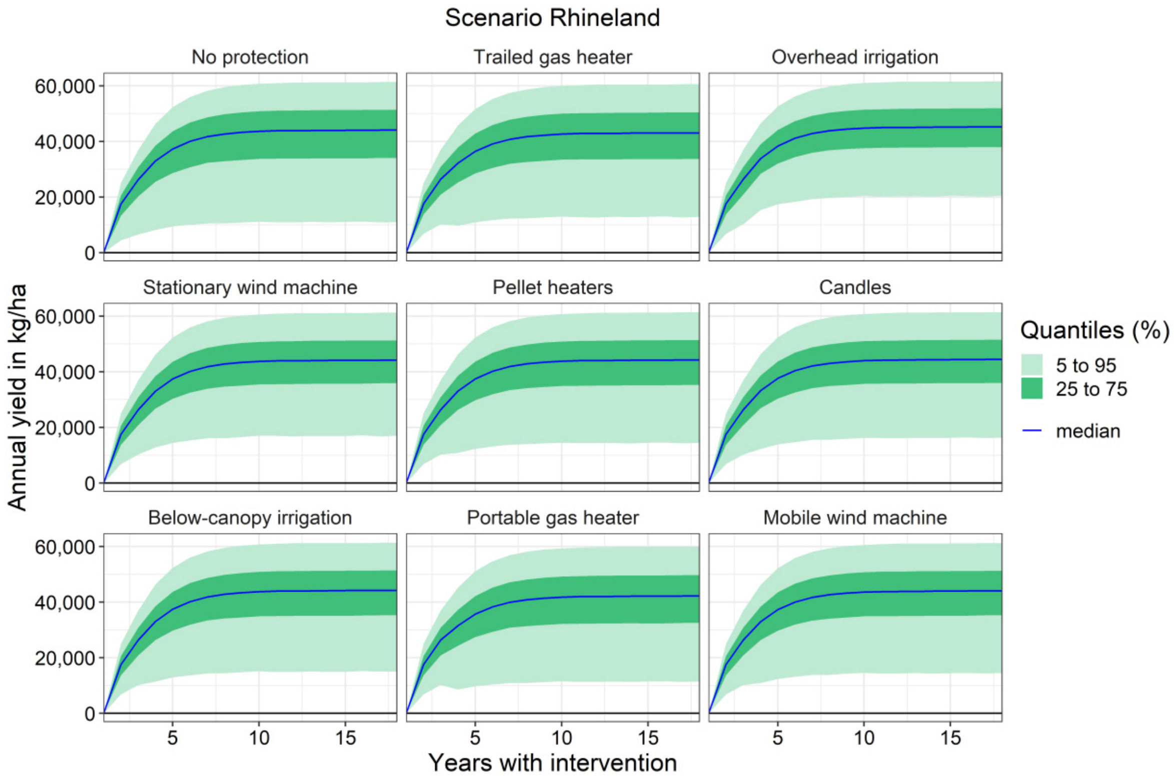
Supporting information 6: Production cost per kg apple in mature orchards (i.e. without the initial investments in orchard and frost protection). Box- and violin plots show the values between the 5 and 95 percent quantiles of 100,000 Monte Carlo simulation runs of the decision model. Green boxes show the results for the Rhineland and orange boxes for the Lake Constance region.

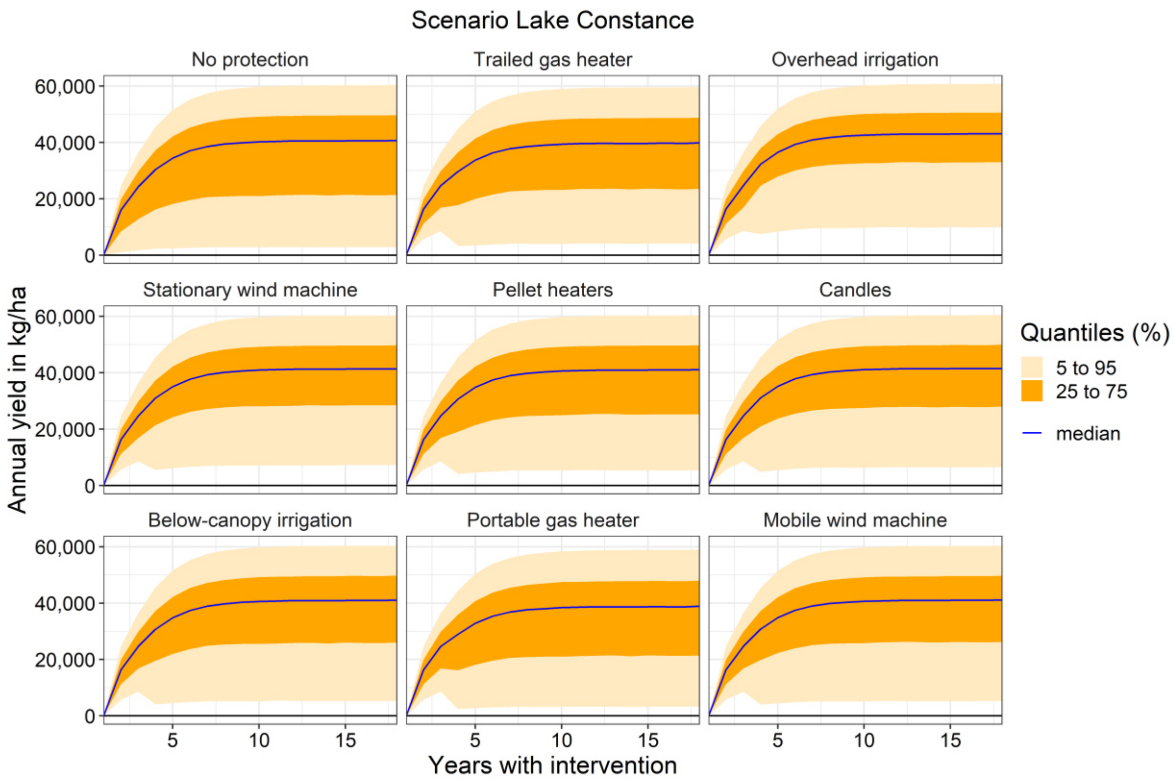
Supporting information 7: Initial investment in frost protection measures



Supporting information 7: Initial investment costs [€/ha] for different frost protection measures, to protect apple orchards in two German apple growing regions. Box- and violin plots show the values between the 5 and 95 percent quantiles of 100,000 Monte Carlo simulation runs of the decision model. Green boxes show the results for the Rhineland and orange boxes for the Lake Constance region.

Supporting information 8: Development of apple yield





Supporting information 8: Probability distributions of projected annual apple yield over 18 years of apple orchard lifetime for several decision options of implementing frost protection measures in apple orchards. The upper plot displays the simulation results for the Rhineland and the bottom plot for the Lake Constance region. The probability distributions were generated with 100,000 Monte Carlo simulation runs of the decision model.

Supplementary Material for Chapter 6

Supporting Information

Spatial distribution of late frost risk in German apple cultivation under changing climatic conditions.

Christine Schmitz[1,2], Lars Caspersen[2], Johannes Kopton[2], Katja Schiffers[2], Eike Luedeling[2]

[1]Dienstleistungszentrum Ländlicher Raum Rheinpfalz, Rheinbach, Germany;

[2]INRES – Horticultural Sciences, University of Bonn, Germany.

Supporting Information 1: Available General Circulation Models

Table 1: General Circulation Models from the CMIP6 dataset, available for Germany under four climate scenarios.

Model	Citation	Scenario			
		SSP1-2.6	SSP2-4.5	SSP3-7.0	SSP5-8.5
ACCESS-CM2	(Dix et al., 2019)	x	x	x	x
AWI-CM-1-1-MR	(Semmler et al., 2018)	x	x	x	x
CanESM5	(Swart et al., 2019)	x			
CIESM	(Huang, 2019)				x
CMCC-ESM2	(Lovato et al., 2021)	x	x		x
CNRM-CM6-1-HR	(Voldoire, 2019)	x	x	x	x
CNRM-CM6-1	(Voldoire, 2018)	x	x	x	x
CNRM-ESM2-1	(Seferian, 2018)	x	x	x	x
EC-Earth3-AerChem	(EC-Earth Consortium (EC-Earth), 2020a)			x	
EC-Earth3-CC	(EC-Earth Consortium (EC-Earth), 2020b)		x		x
EC-Earth3-Veg-LR	(EC-Earth Consortium (EC-Earth), 2020c)	x	x	x	x
FGOALS-g3	(Li, 2019)	x	x	x	x
FIO-ESM-2-0	(Song et al., 2019)	x	x		x
GFDL-ESM4	(Krasting et al., 2018)	x	x	x	x
INM-CM4-8	(Volodin et al., 2019a)	x	x	x	x
INM-CM5-0	(Volodin et al., 2019b)	x	x	x	x
IPSL-CM6A-LR	(Boucher et al., 2018)	x	x	x	x
MIROC-ES2L	(Hajima et al., 2019)	x	x	x	x
MIROC6	(Tatebe and Watanabe, 2018)	x	x	x	x
MPI-ESM1-2-LR	(Wieners et al., 2019)	x	x	x	x
MRI-ESM2-0	(Yukimoto et al., 2019)	x	x	x	x
NESM3	(Cao and Wang, 2019)	x	x		x

Supporting Information 2: Fitted PhenoFlex Parameters

Table 2: Fitting result for ten repetitions of PhenoFlex fitting for apple bloom in Germany. Repetition one (green shaded) was used for all further analysis.

repetition	cultivar	yc	zc	s1	Tu	theta_c	tau	piec	Tf	Tb	slope	theta_star	Tc
1	early	64.97	282.10	0.26	19.08	285.89	40.46	37.68	2.04	4.65	1.25	279	36
1	late	54.74	321.34	0.29	23.19	286.14	46.43	42.92	2.26	2.24	1.37	279	36
2	early	51.99	281.44	0.35	24.31	285.98	45.13	41.42	3.50	2.11	1.24	279	36
2	late	35.87	269.65	0.34	17.73	284.95	47.33	43.94	5.34	6.80	1.21	279	36
3	early	51.00	251.84	0.30	25.13	285.73	47.11	43.63	3.35	2.35	1.27	279	36
3	late	41.26	255.86	0.14	16.36	284.92	47.48	46.96	5.22	6.82	1.22	279	36
4	early	44.43	248.60	0.22	17.27	285.82	47.75	44.98	4.11	6.57	1.65	279	36
4	late	55.11	286.73	0.43	22.61	285.96	46.75	43.11	3.36	3.34	1.35	279	36
5	early	50.42	237.20	0.94	26.15	285.57	44.84	42.24	2.89	2.56	1.71	279	36
5	late	63.20	246.88	0.25	23.11	286.12	40.35	37.33	2.36	4.13	1.60	279	36
6	early	44.45	251.35	0.78	26.35	285.20	43.94	42.86	4.35	2.18	1.30	279	36
6	late	62.77	248.10	0.59	24.38	285.31	33.37	32.47	3.06	3.77	2.13	279	36
7	early	51.99	278.14	0.28	21.80	284.73	44.43	44.50	2.37	3.22	1.37	279	36
7	late	36.74	266.58	0.25	17.74	284.63	47.33	47.08	4.83	6.73	1.25	279	36
8	early	50.71	211.62	0.37	24.56	286.62	47.58	26.57	3.29	3.88	1.27	279	36
8	late	36.05	263.50	0.23	17.64	284.61	47.88	47.15	5.27	6.56	1.27	279	36
9	early	40.06	198.31	0.20	24.70	284.48	47.26	47.85	4.13	3.99	1.24	279	36
9	late	44.73	254.73	0.16	17.71	284.54	47.38	47.17	2.58	6.71	1.26	279	36
10	early	36.92	246.07	0.26	17.65	284.71	47.44	42.75	3.85	6.54	1.25	279	36
10	late	50.59	269.71	0.73	25.84	285.21	44.31	42.52	4.81	2.31	1.24	279	36

Supporting Information 3: Overview of all packages used for modelling

Table 1: List of all R packages used in modeling the frost damage frequency and plotting the result.

Package name	Citation
beepr	(Bååth, 2024)
chillR	(Luedeling et al., 2024)
evalpheno	(Caspersen, 2025b)
ggplot2	(Wickham et al., 2022)
ggspatial	(Dunnington, 2023)
grid	Part of base R (R Core Team, 2024)
gstat	(Pebesma, 2004)
LarsChill	(Caspersen, 2025a)
leaflet	(Cheng et al., 2024)
maps	(Becker et al., 2025)
optparse	(Davis, 2024)
png	(Urbanek, 2022)
R.utils	(Bengtsson, 2025)
raster	(Hijmans, 2025)
rasterVis	(Perpi and Hijmans, 2023)
rnaturalearth	(Massicotte and South, 2023)
rnaturalearthdata	(South et al., 2024)
rnaturalearthhires	(South et al., 2025)
scam	(Pya, 2023)
sf	(Pebesma and Bivand, 2023)
sp	(Pebesma and Bivand, 2005)
sqldf	(Grothendieck, 2017)
stars	(Pebesma and Bivand, 2023)
stringr	(Wickham, 2023)
terra	(Hijmans, 2023)
tidyverse	(Wickham et al., 2019)
viridis	(Garnier et al., 2023)

Supporting Information 4: Frost probability maps for early ripening apple varieties for pathway SSP1-2.6

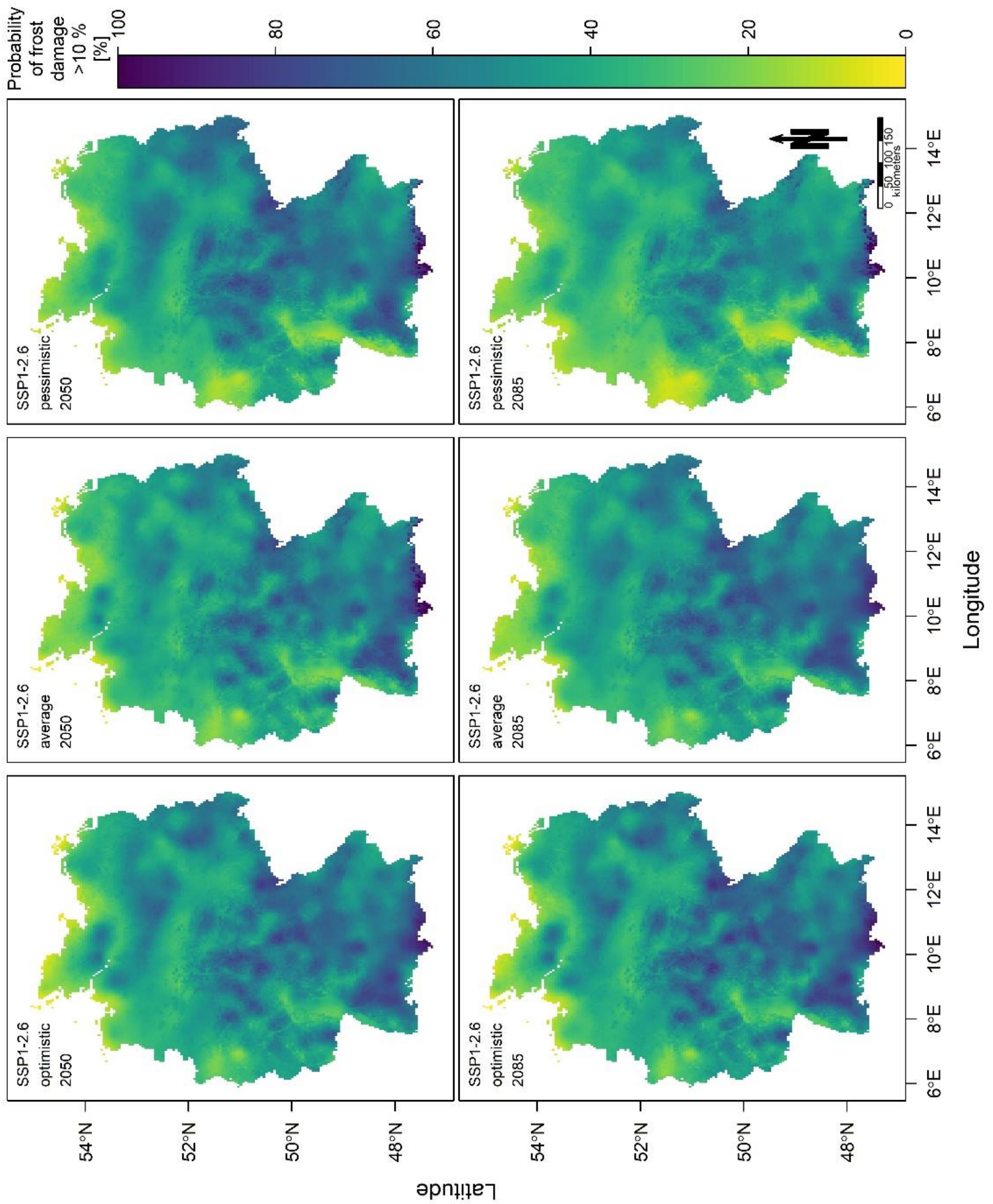


Figure 1: Probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for early-ripening apple varieties in Germany for SSP1-2.6 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

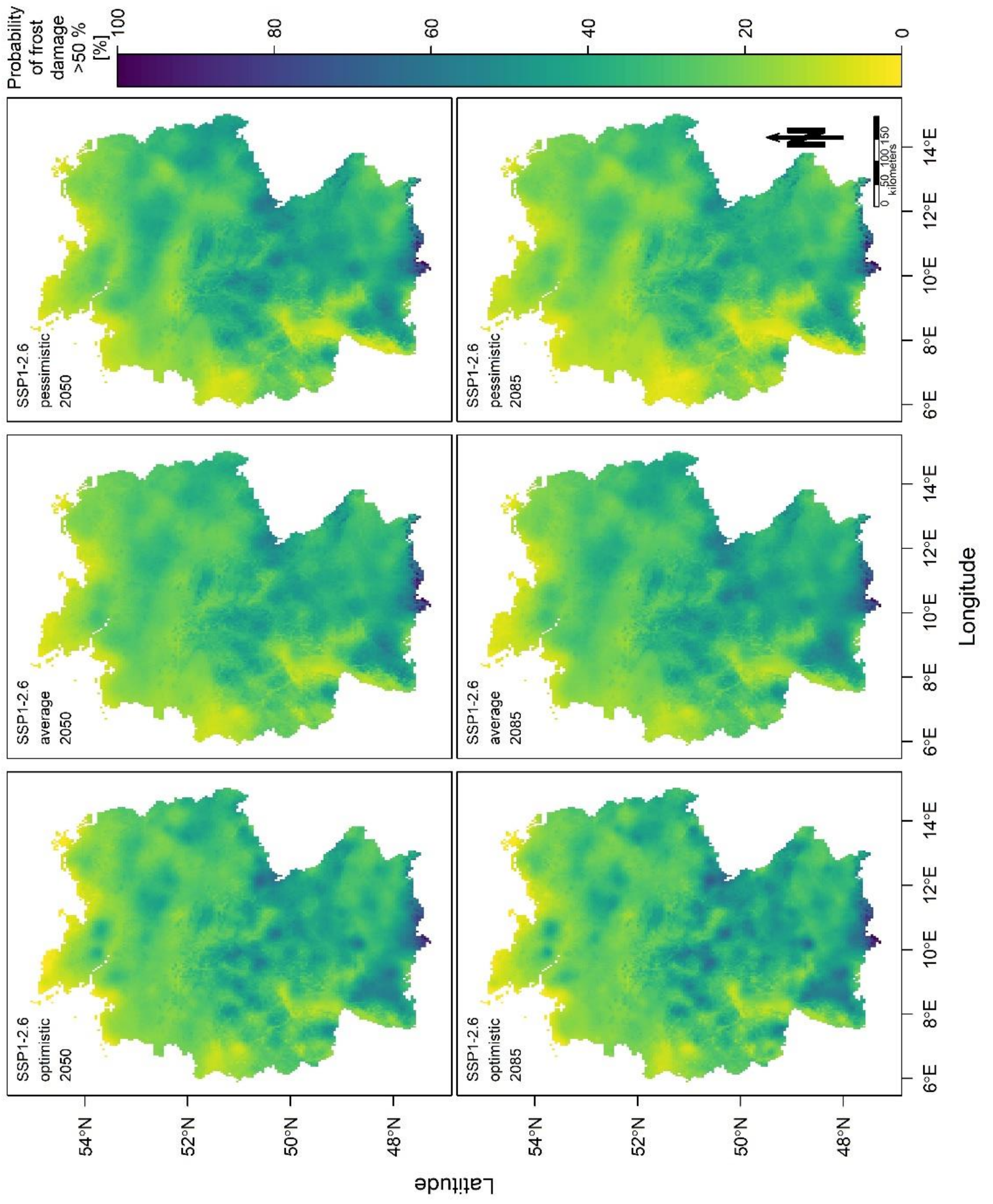


Figure 2: Probability of frost damage affecting more than 50% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for early-ripening apple varieties in Germany for SSP1-2.6 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

Supporting Information 5: Frost probability maps for early ripening apple varieties for pathway SSP2-4.5

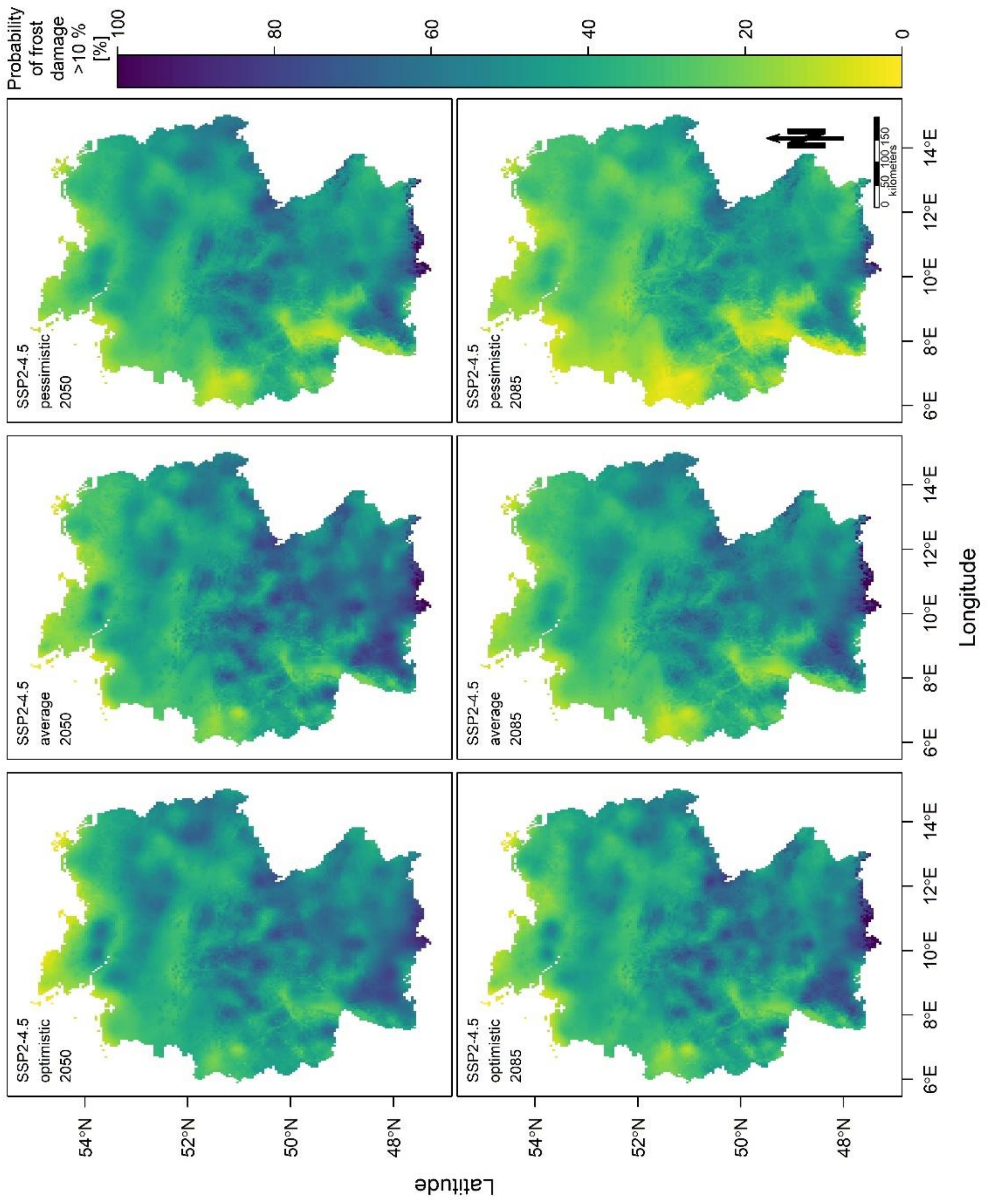


Figure 3: Probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for early-ripening apple varieties in Germany for SSP2-4.5 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

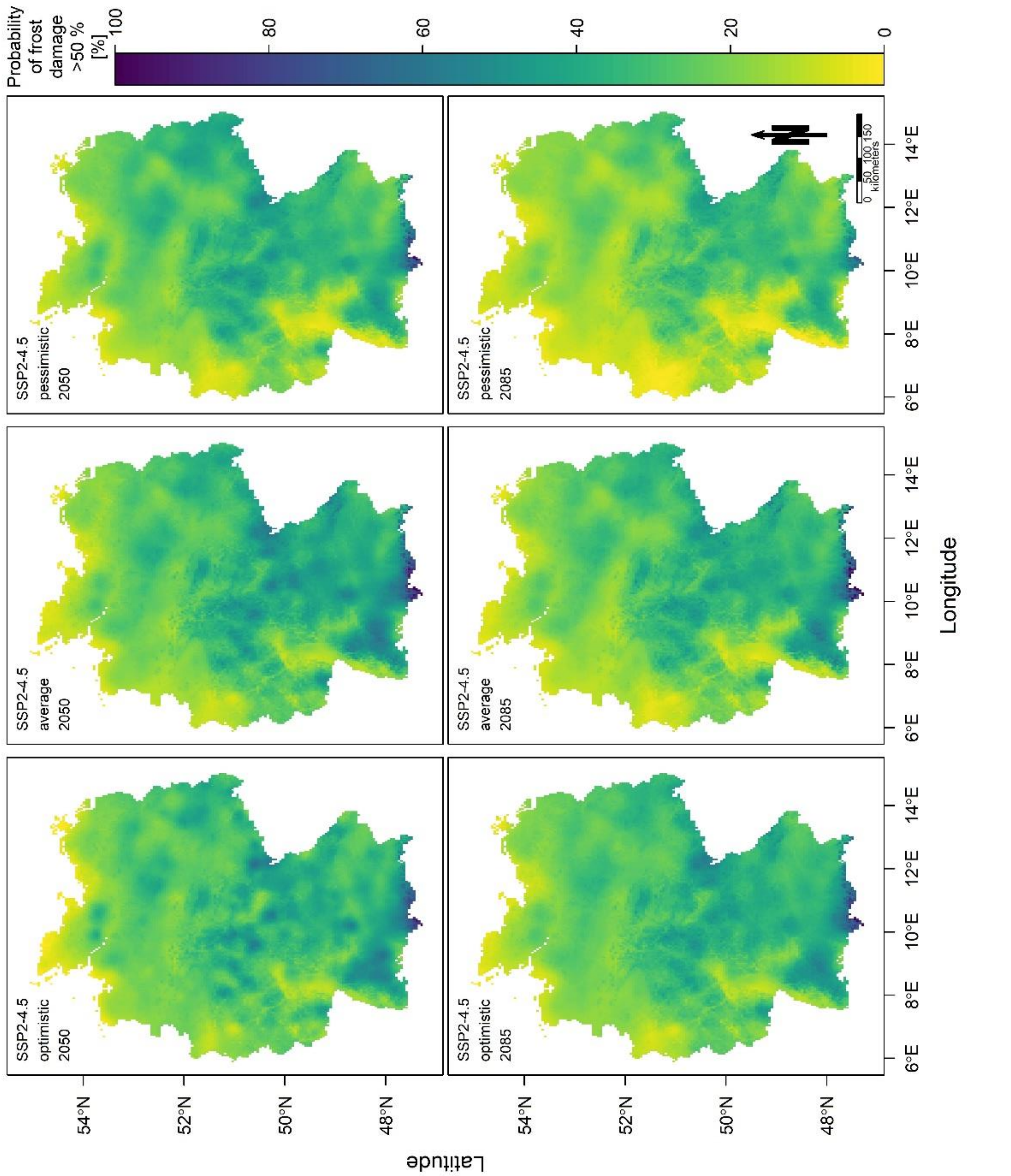


Figure 4: Probability of frost damage affecting more than 50% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for early-ripening apple varieties in Germany for SSP2-4.5 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >50% and have a cell size of 0.05° (about 3.5x5.5 km)

Supporting Information 6: Frost probability maps for early ripening apple varieties for pathway SSP3-7.0

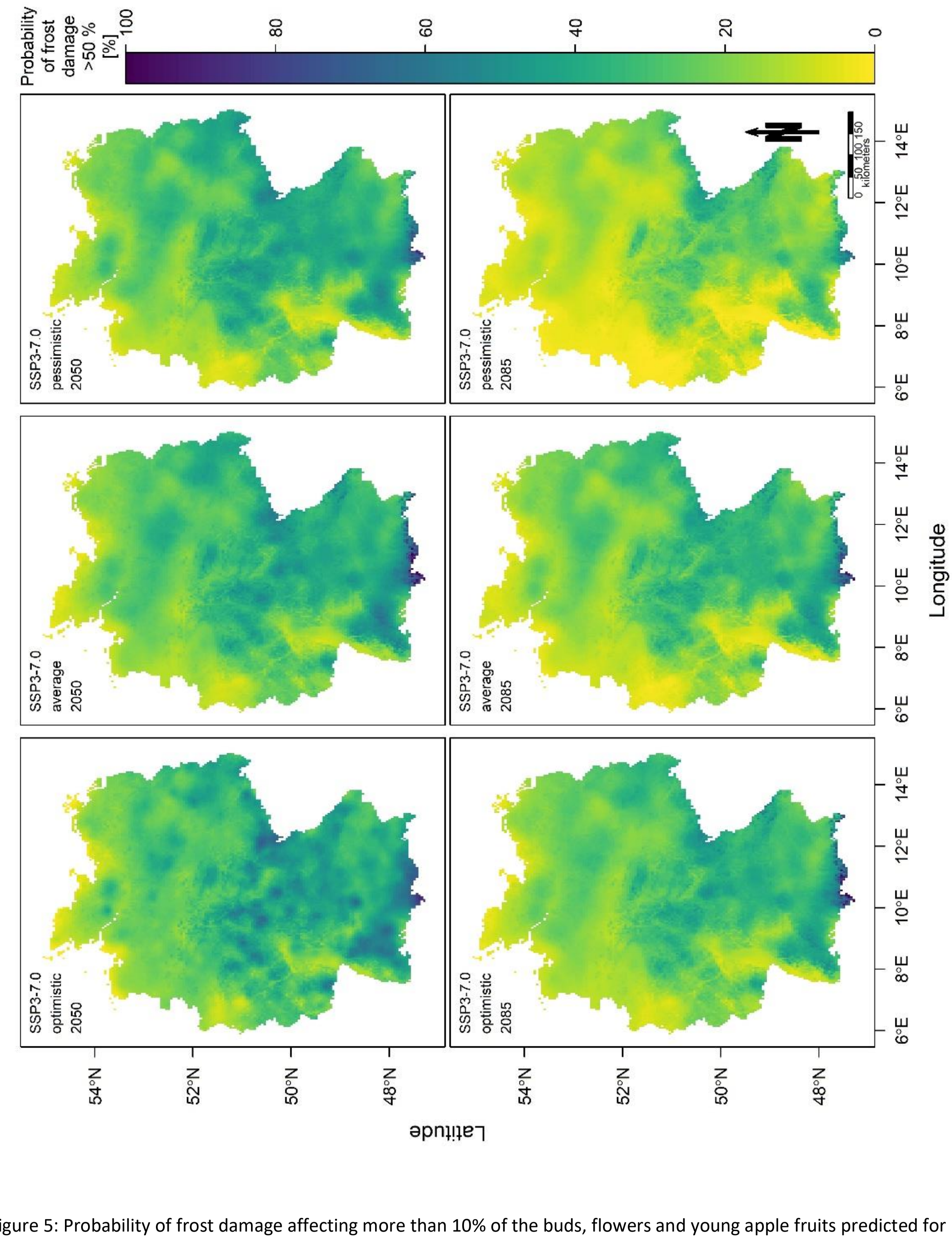


Figure 5: Probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for early-ripening apple varieties in Germany for SSP3-7.0 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

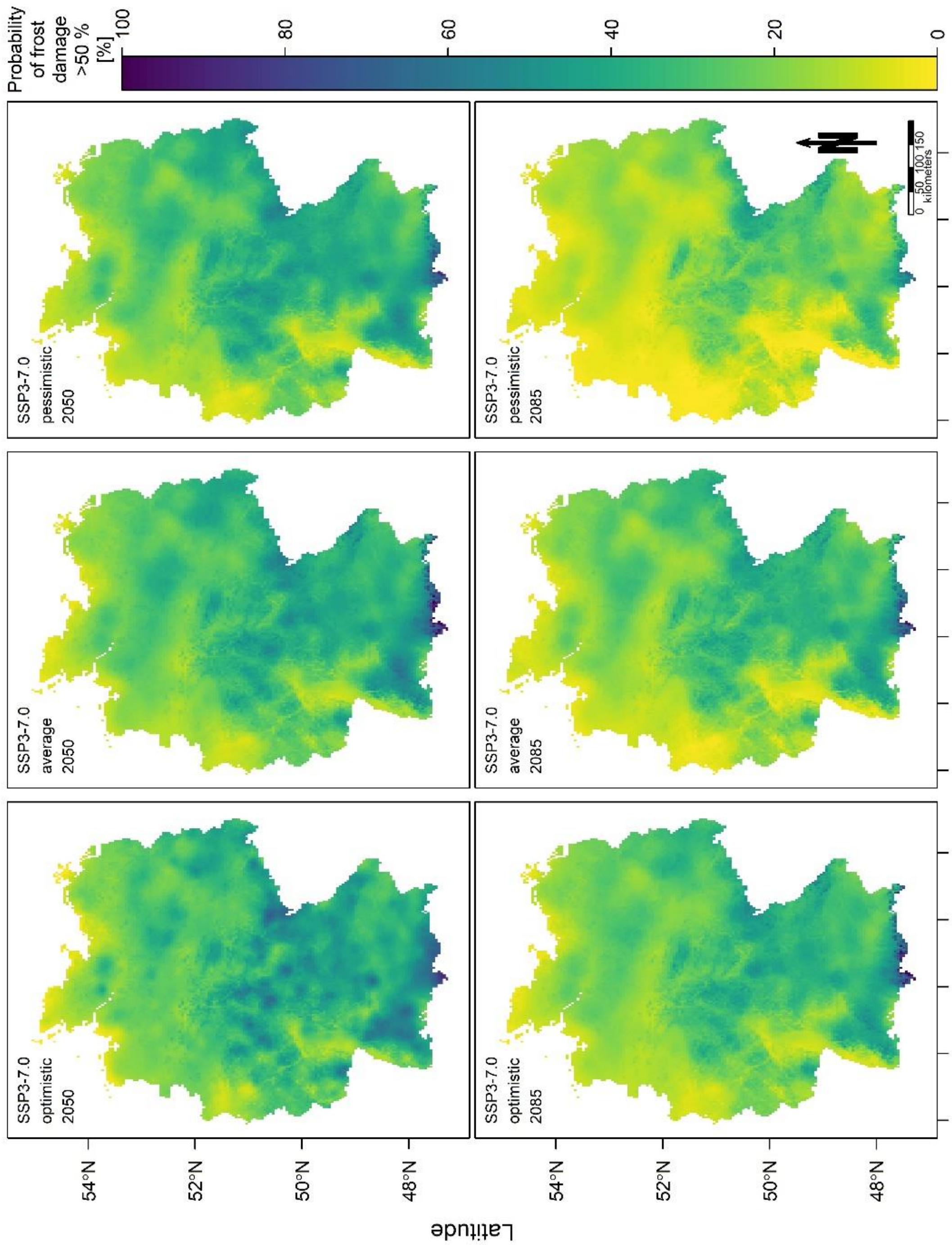


Figure 6: Probability of frost damage affecting more than 50% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for early-ripening apple varieties in Germany for SSP3-7.0 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >50% and have a cell size of 0.05° (about 3.5x5.5 km)

Supporting Information 7: Frost probability maps for early ripening apple varieties for pathway SSP5-8.5

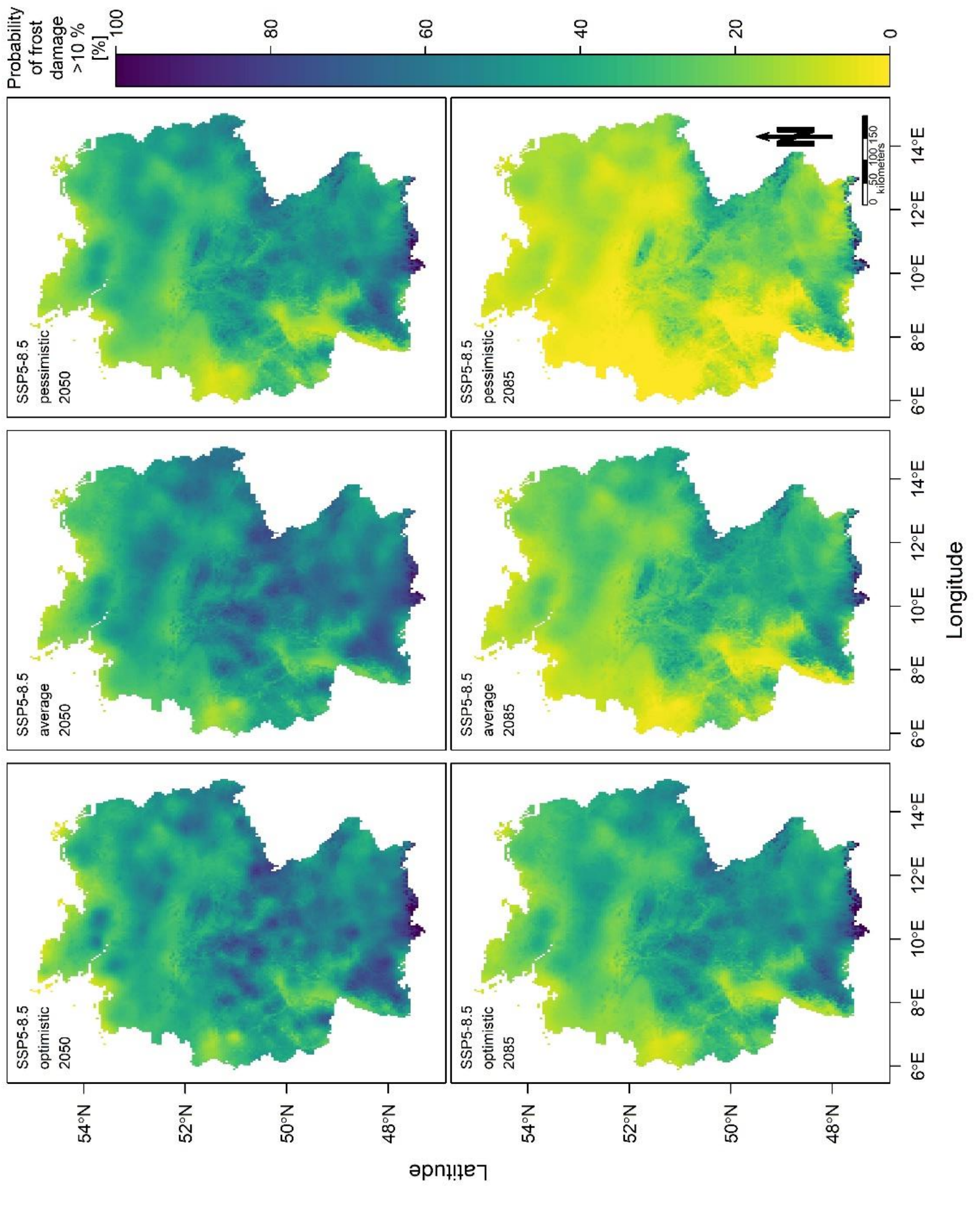


Figure 7: Probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for early-ripening apple varieties in Germany for SSP5-8.5 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

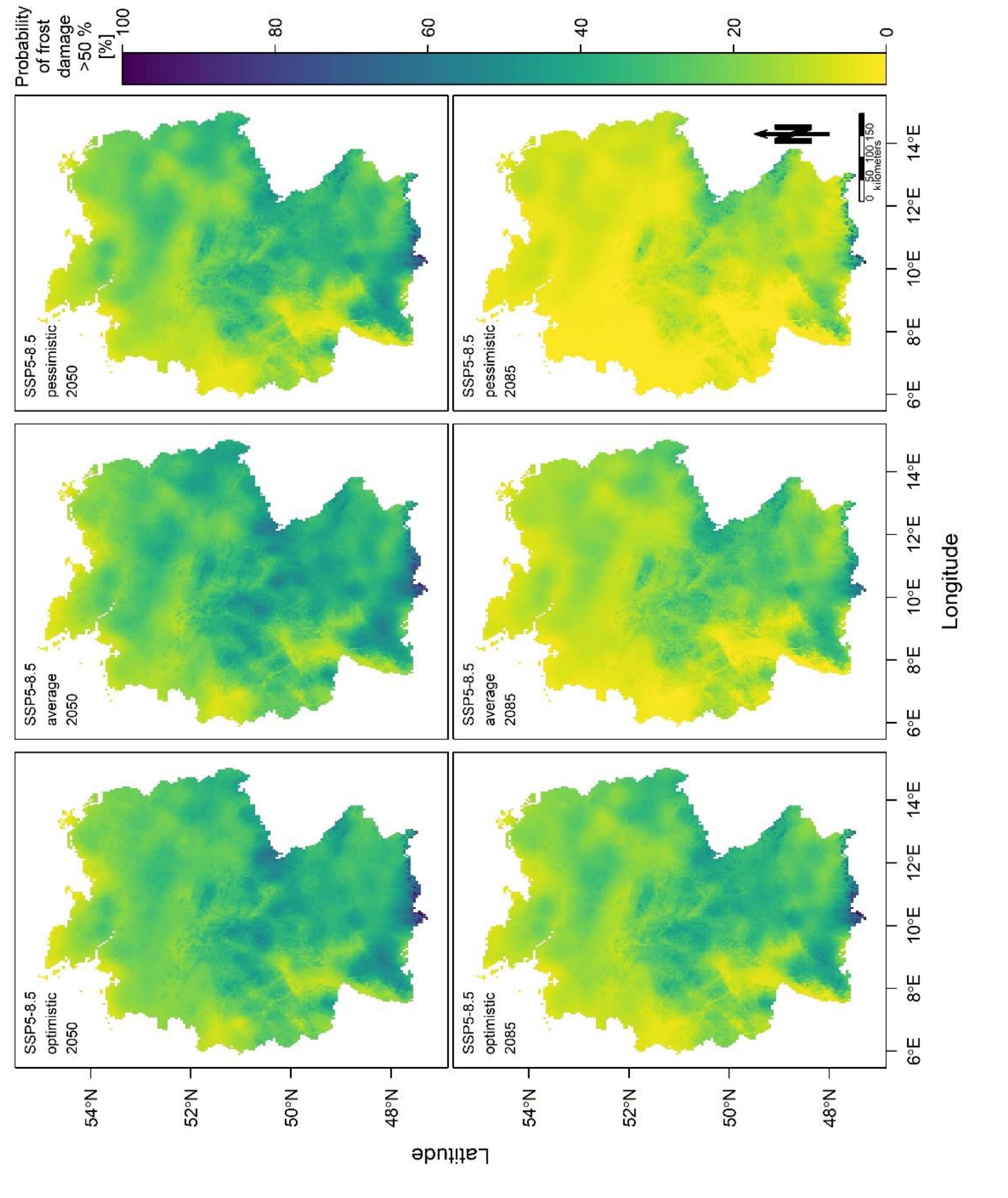


Figure 8: Probability of frost damage affecting more than 50% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for early-ripening apple varieties in Germany for SSP5-8.5 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >50% and have a cell size of 0.05° (about 3.5x5.5 km)

Supporting Information 8: Frost probability maps for late ripening apple varieties for pathway SSP1-2.6

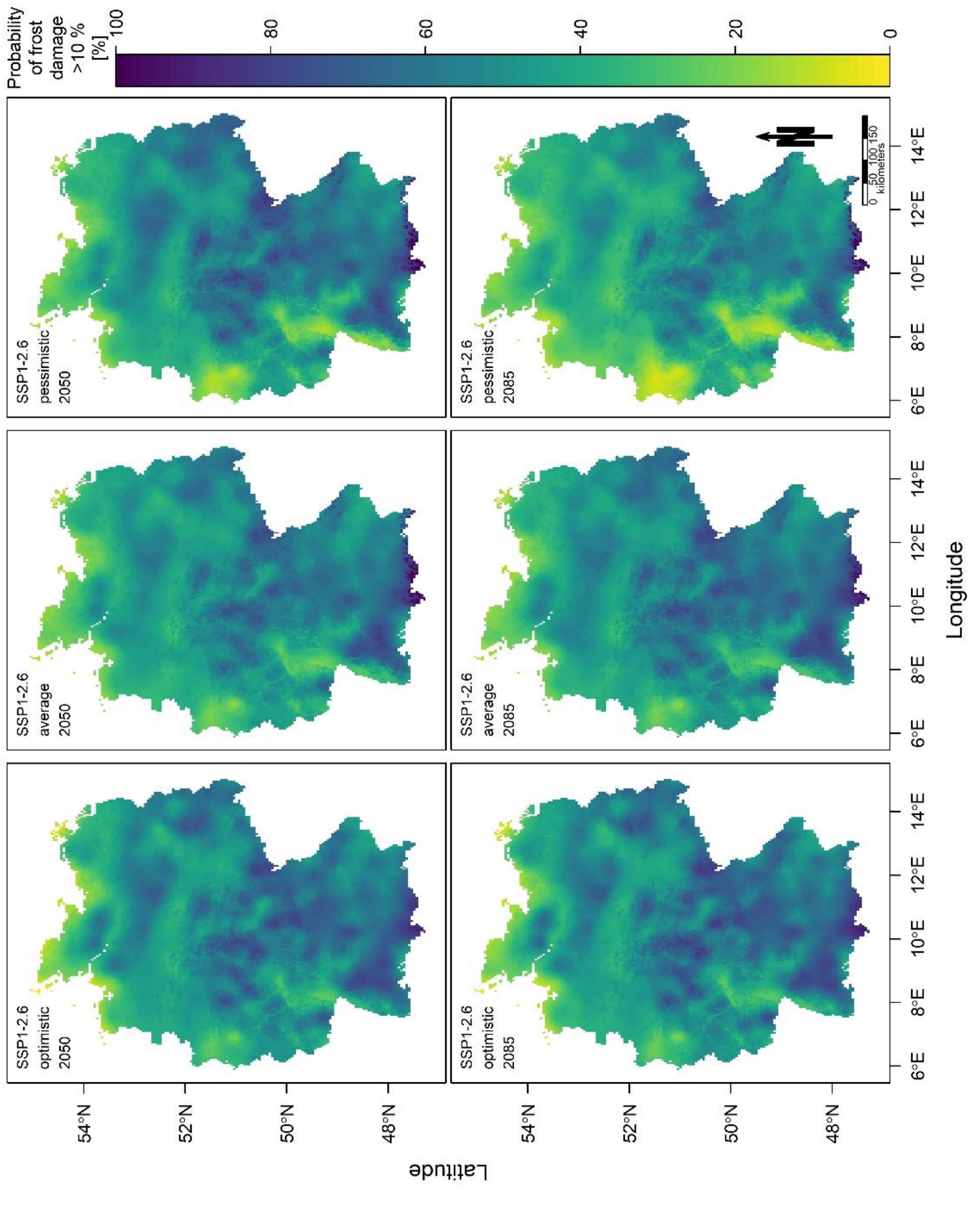


Figure 9: Probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for late-ripening apple varieties in Germany for SSP1-2.6 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

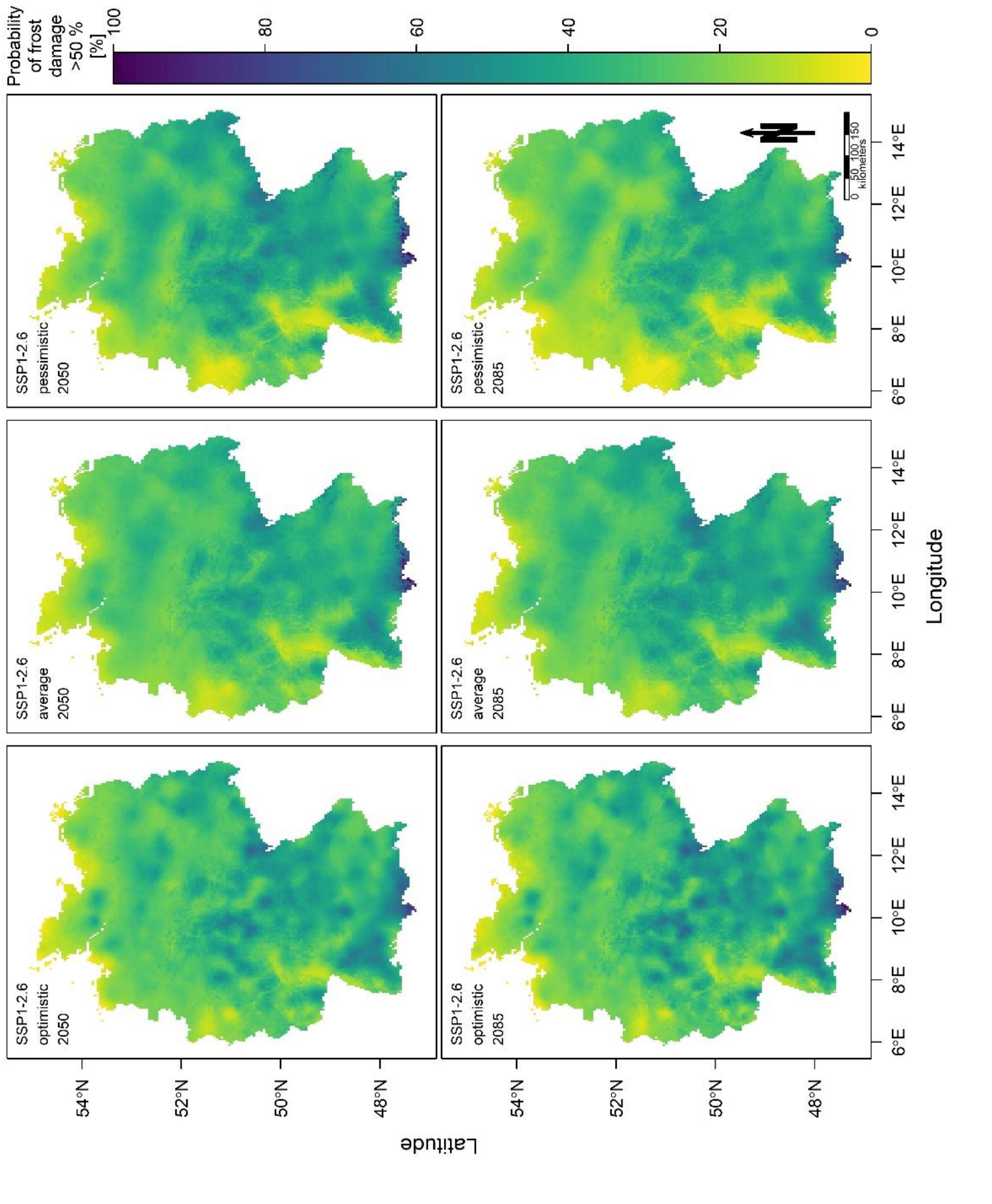


Figure 10: Probability of frost damage affecting more than 50% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for late-ripening apple varieties in Germany for SSP1-2.6 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >50% and have a cell size of 0.05° (about 3.5x5.5 km)

Supporting Information 9: Frost probability maps for late ripening apple varieties for pathway SSP2-4.5

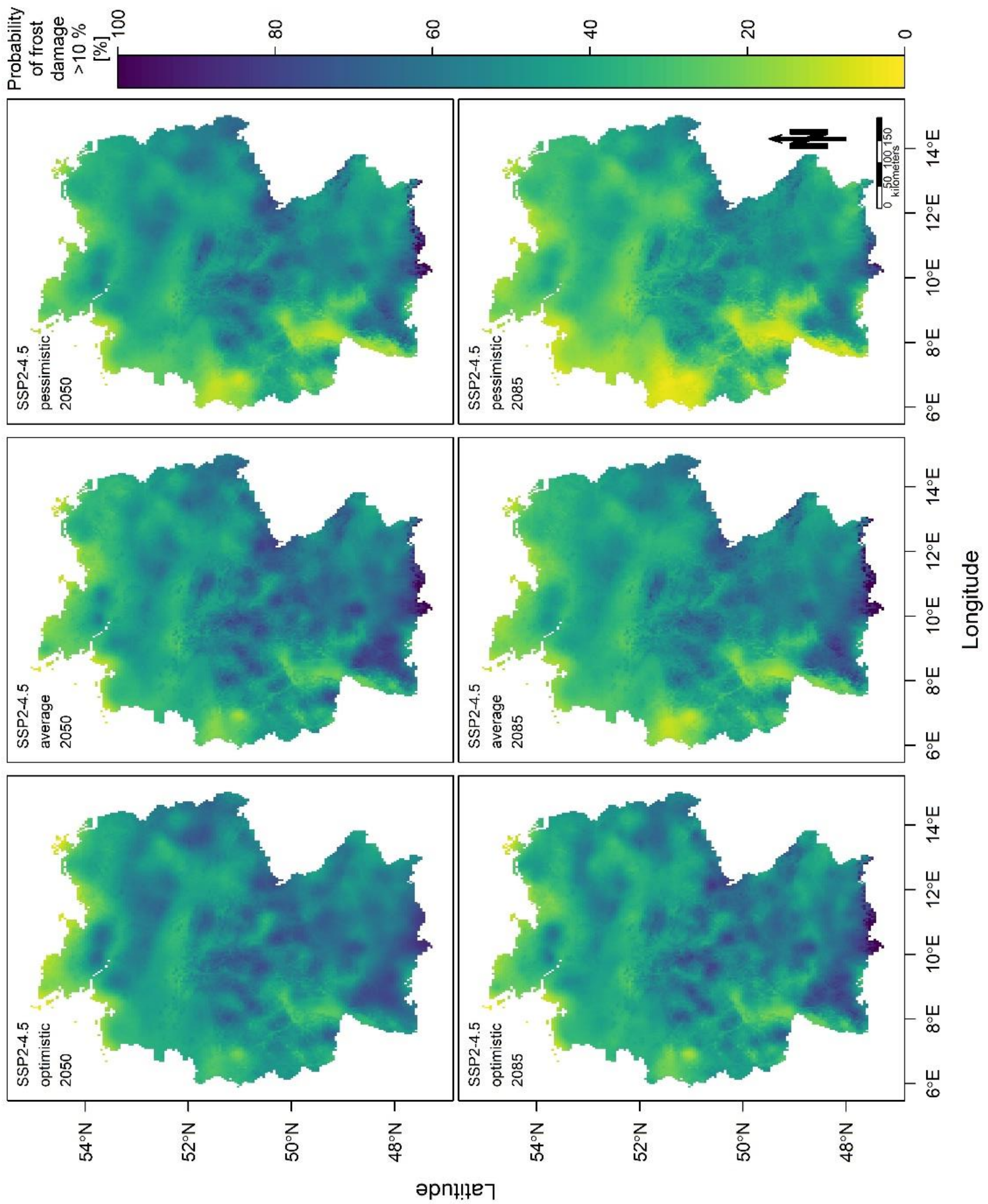


Figure 11: Probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for late-ripening apple varieties in Germany for SSP2-4.5 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

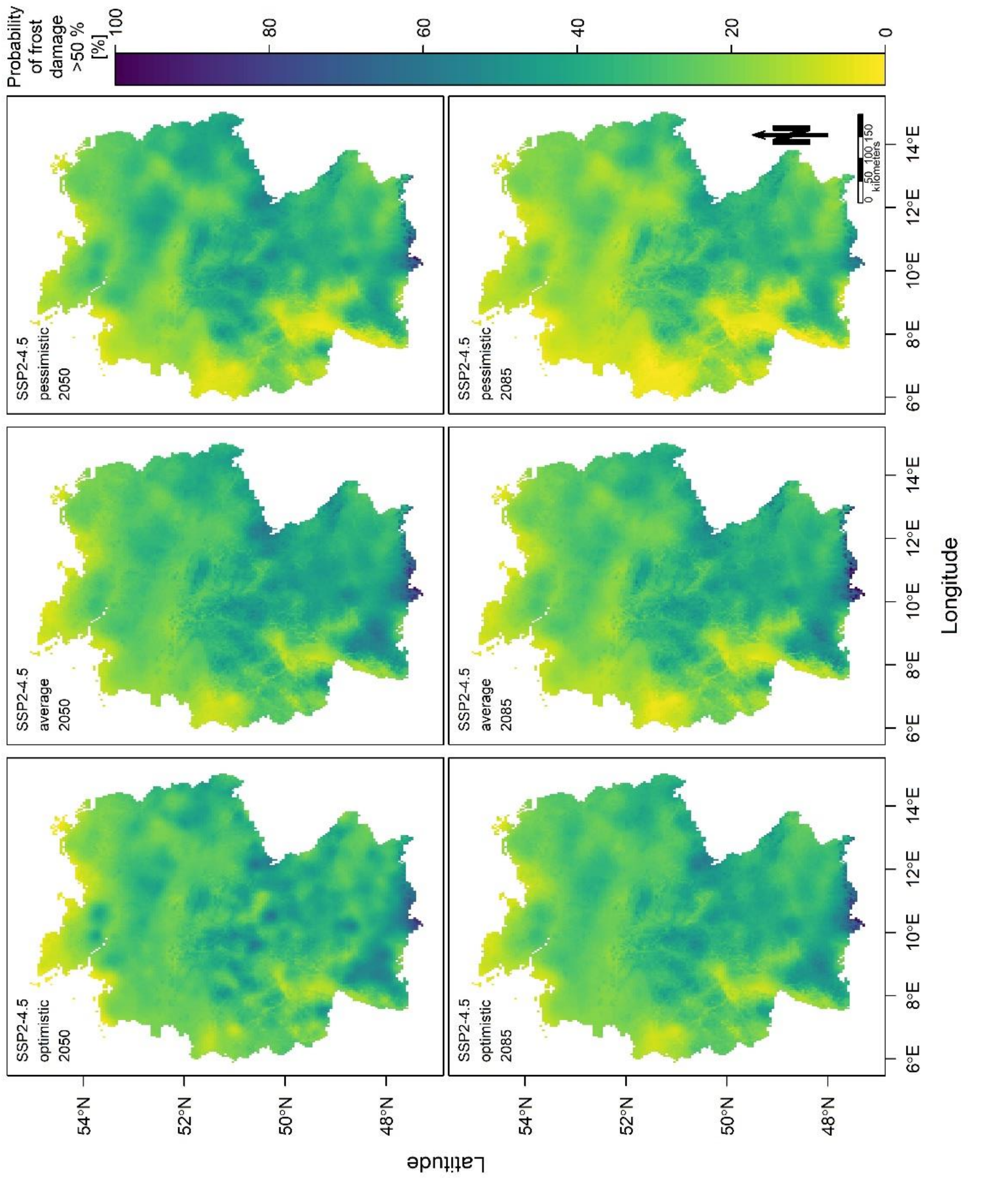


Figure 12: Probability of frost damage affecting more than 50% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for late-ripening apple varieties in Germany for SSP2-4.5 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >50% and have a cell size of 0.05° (about 3.5x5.5 km)

Supporting Information 10: Frost probability maps for late ripening apple varieties for pathway SSP3-7.0

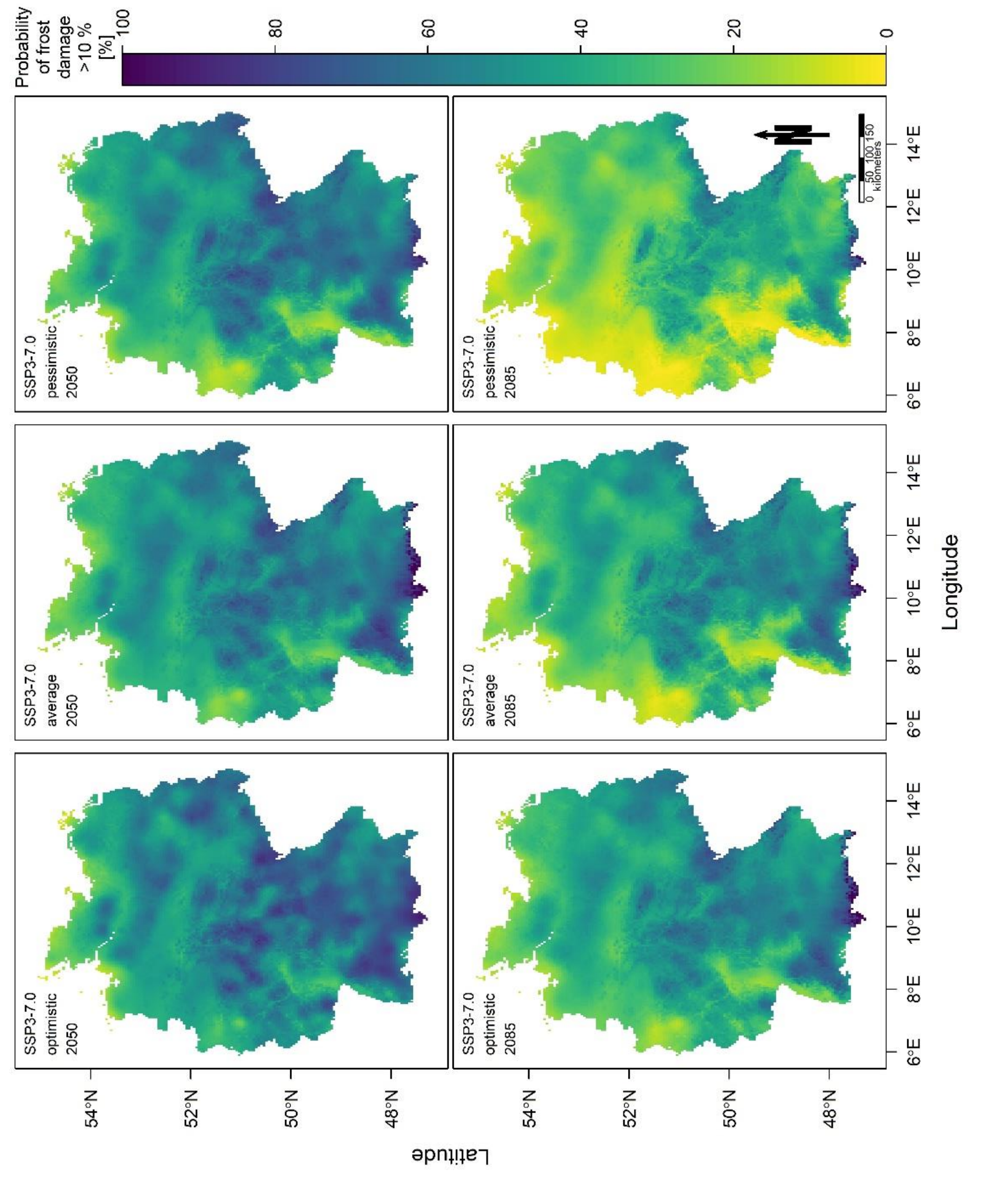


Figure 13: Probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for late-ripening apple varieties in Germany for SSP3-7.0 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

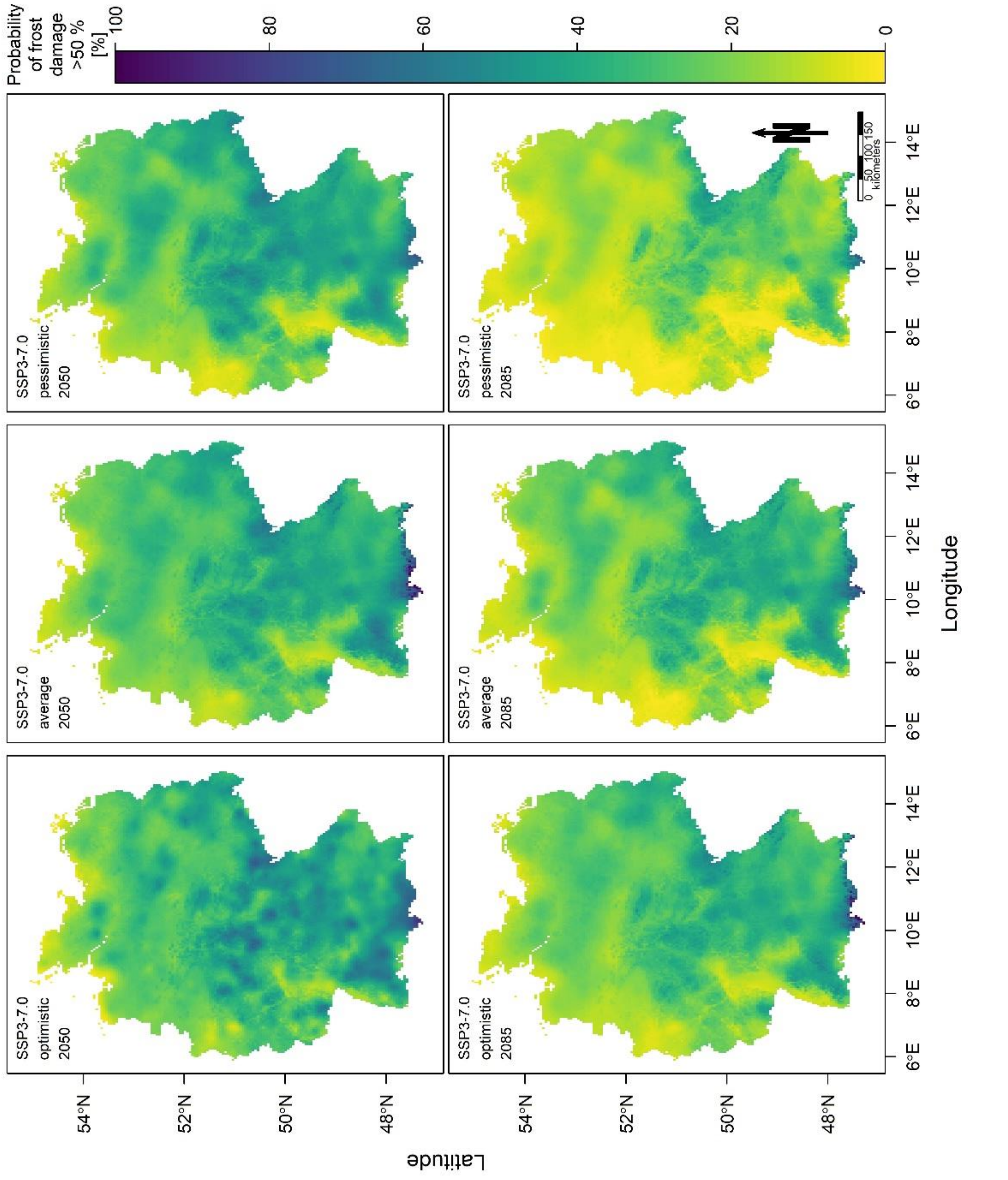


Figure 14: Probability of frost damage affecting more than 50% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for late-ripening apple varieties in Germany for SSP3-7.0 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >50% and have a cell size of 0.05° (about 3.5x5.5 km)

Supporting Information 11: Frost probability maps for late ripening apple varieties for pathway SSP5-8.5

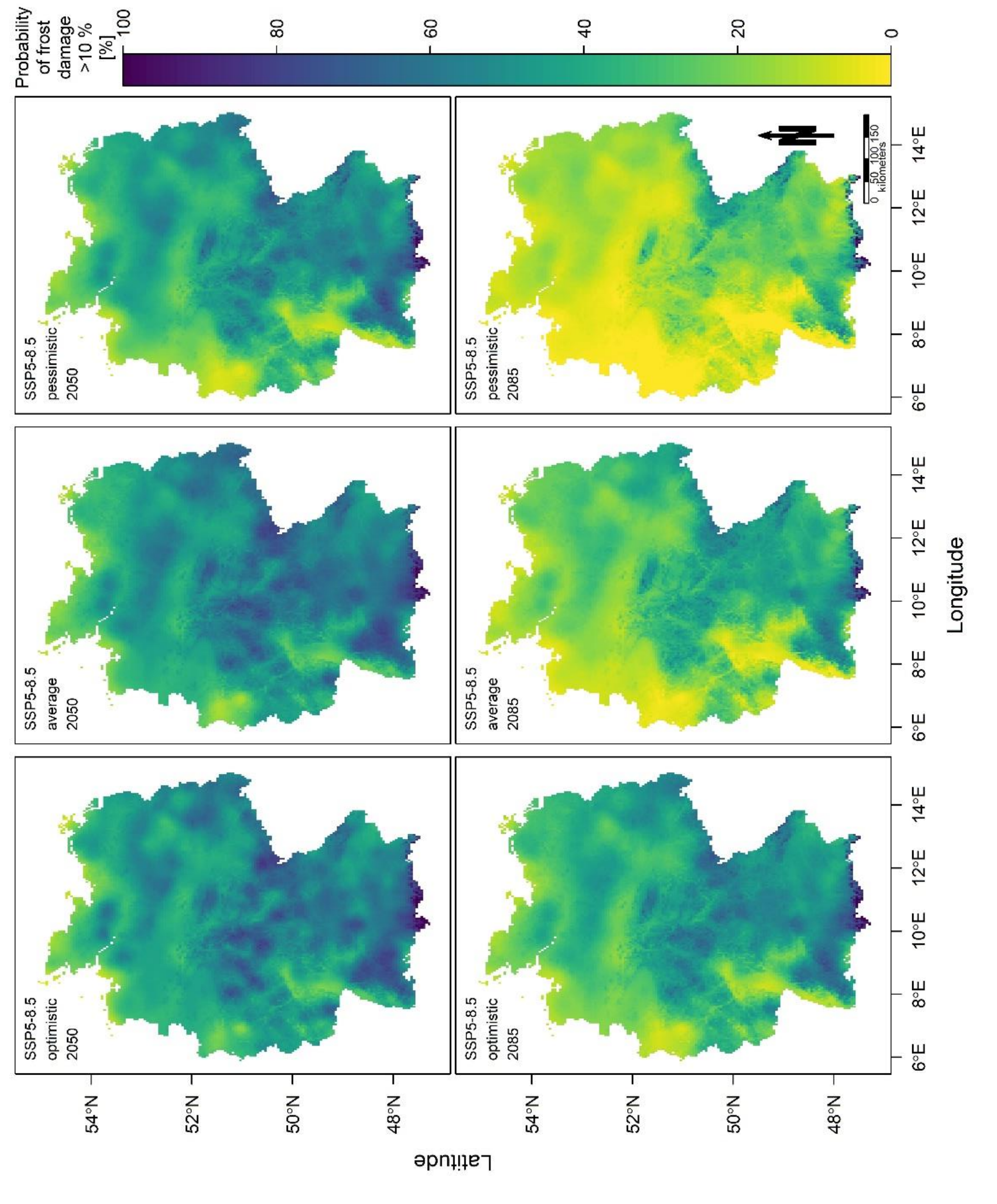


Figure 15: Probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for late-ripening apple varieties in Germany for SSP5-8.5 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

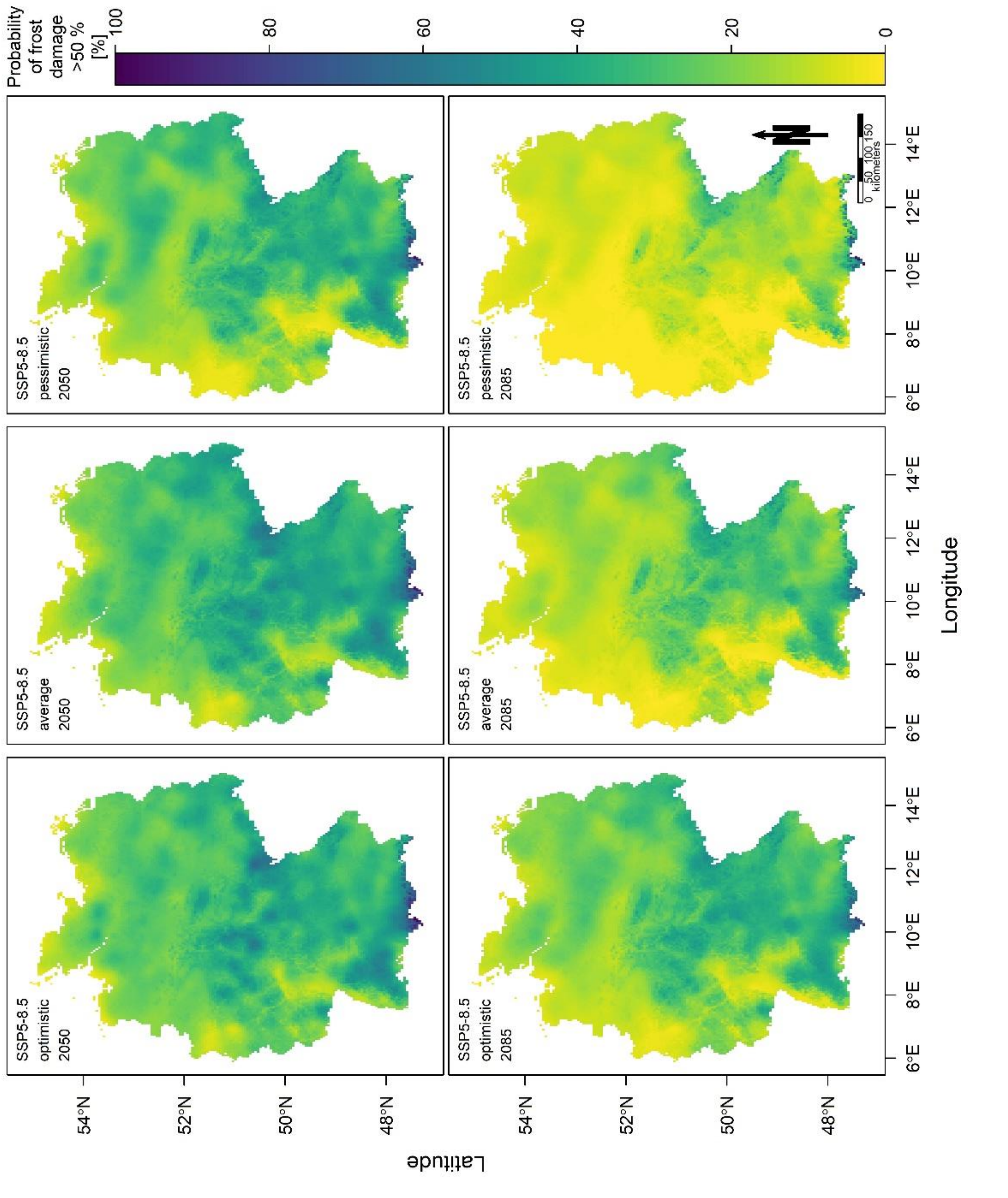


Figure 16: Probability of frost damage affecting more than 50% of the buds, flowers and young apple fruits predicted for 2050 (top) and 2085 (bottom) for late-ripening apple varieties in Germany for SSP5-8.5 and the summarized GCMs optimistic (left) average (middle) and pessimistic (right). Maps are based on interpolated data for the probability of frost damage >50% and have a cell size of 0.05° (about 3.5x5.5 km)

Supporting Information 12: Change in frost damage probability in the future

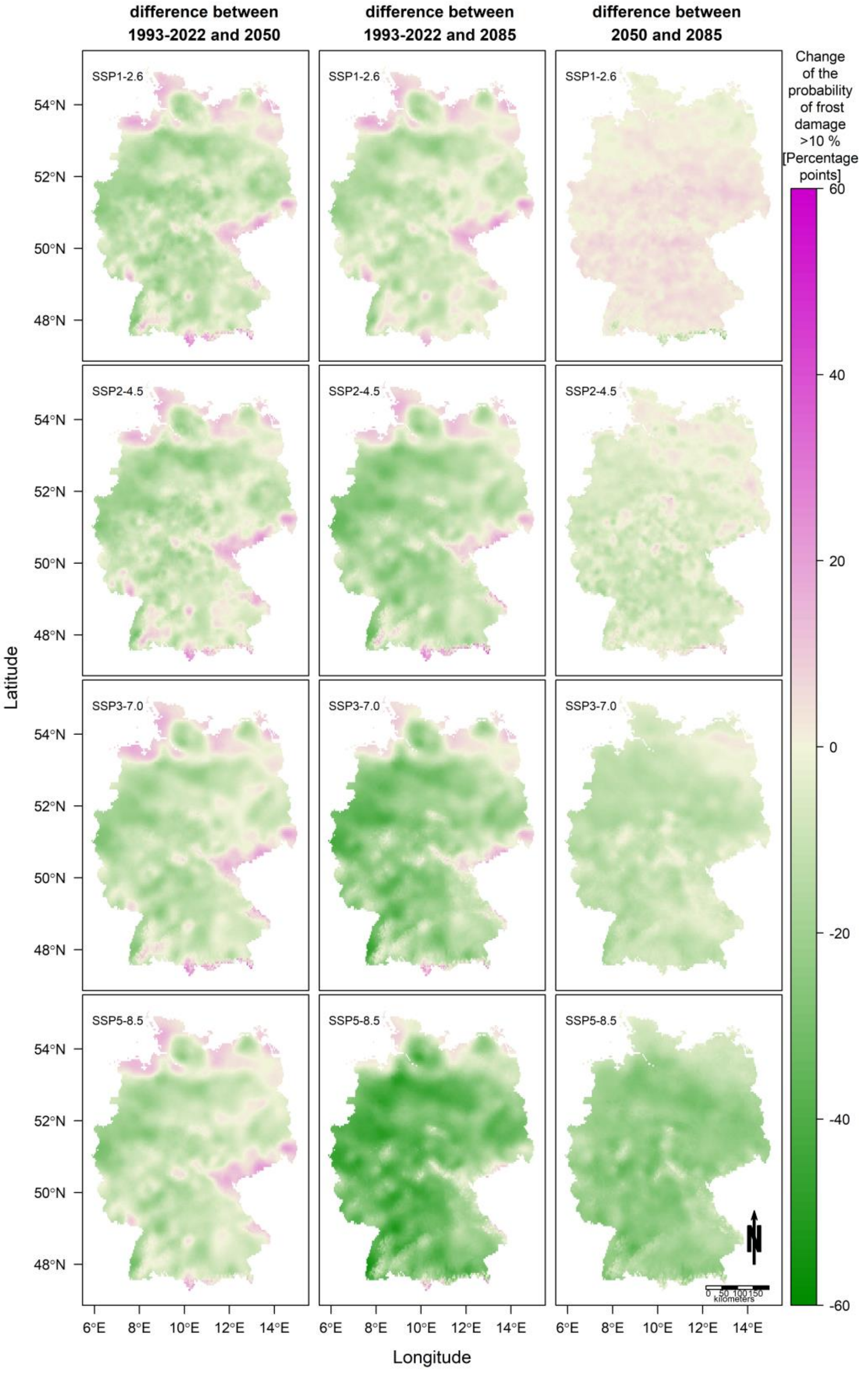


Figure 17: Change in the probability of frost damage affecting more than 10% of the buds, flowers and young apple fruits between the recent past (1993-2022) and 2050 (left column), recent past (1993-2022) and 2085 (middle column) as well as between 2050 and 2085 (right column) for early-ripening apple varieties in Germany assuming different SSPs (rows) and the average model. Negative values (green) indicate a decreasing frost damage frequency and positive values (pink) indicate an increasing frost damage frequency. Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

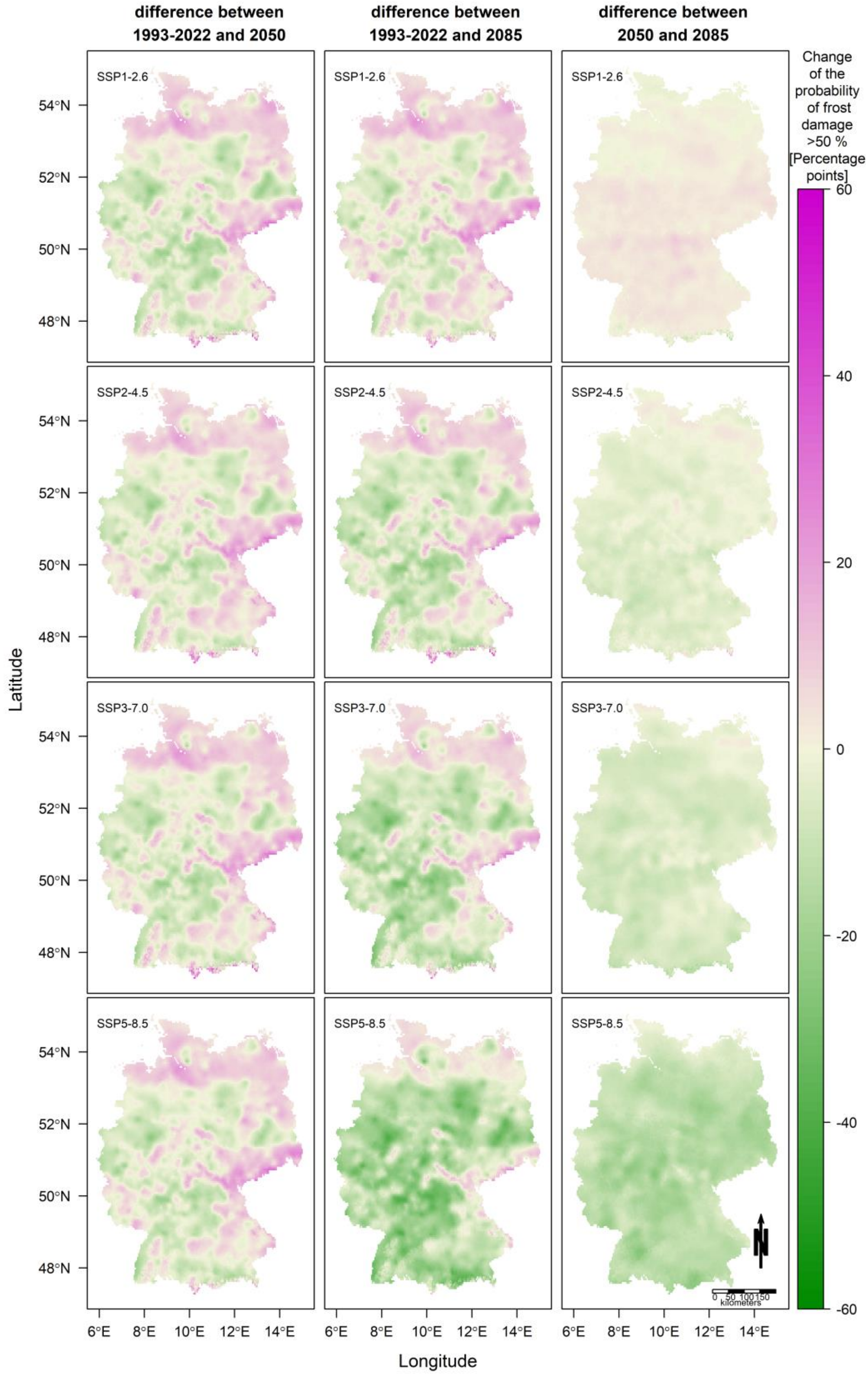


Figure 18: Change in the probability of frost damage affecting more than 50% of the buds, flowers and young apple fruits between the recent past (1993-2022) and 2050 (left column), recent past (1993-2022) and 2085 (middle column) as well as between 2050 and 2085 (right column) for early-ripening apple varieties in Germany assuming different SSPs (rows) and the average model. Negative values (green) indicate a decreasing frost damage frequency and positive values (pink) indicate an increasing frost damage frequency. Maps are based on interpolated data for the probability of frost damage >10% and have a cell size of 0.05° (about 3.5x5.5 km)

Supporting Information 13: Temperature response for the chill and heat sub models of PhenoFlex

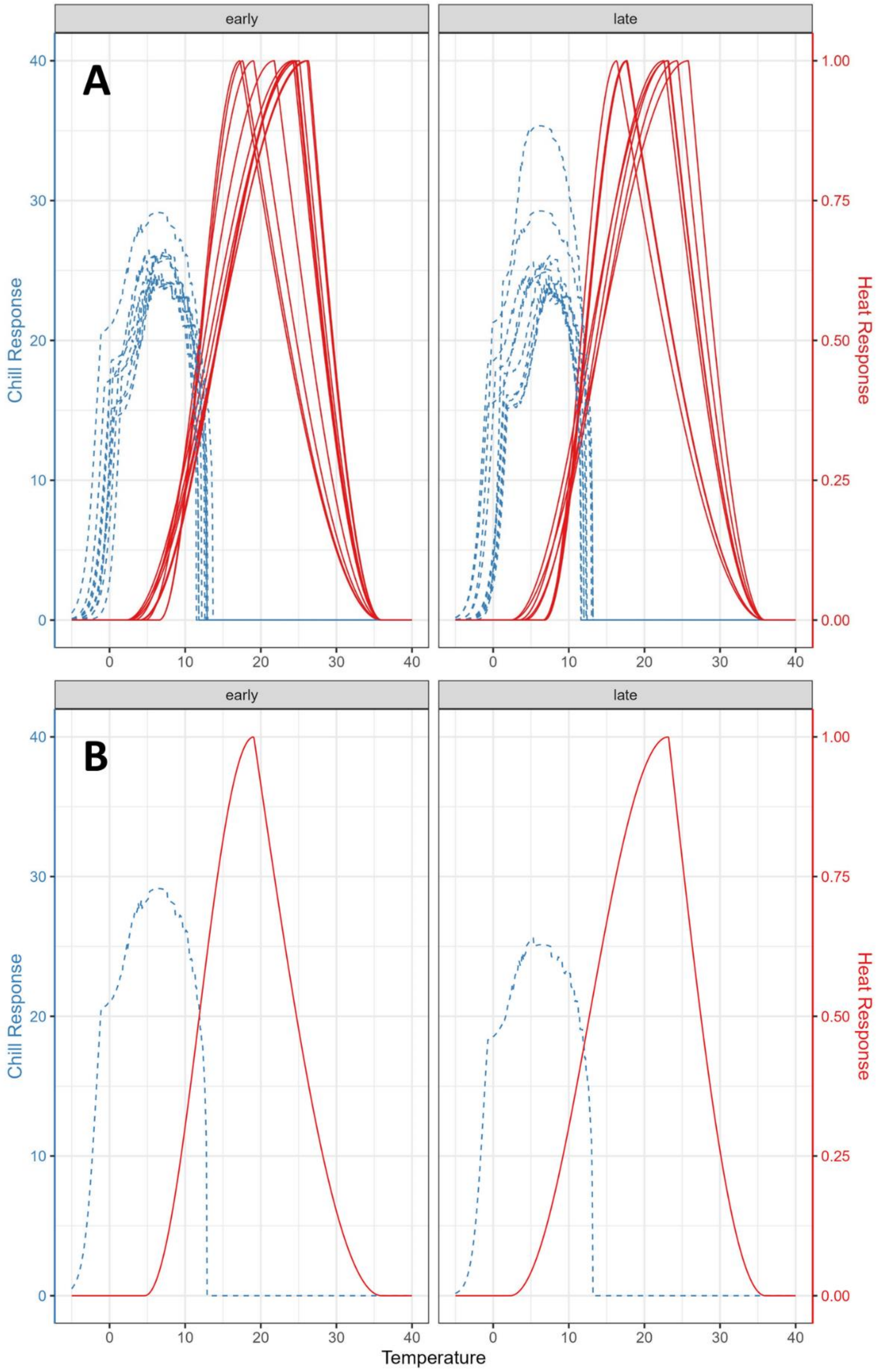


Figure 4: Temperature response (arbitrary units) for the chill (blue) and heat (red) sub models of PhenoFlex for the fitted parameters of all parametrization repetitions (A) and the first repletion (B) which was used in all further modeling steps. The left column shows the results for early-ripening and the right column for late-ripening apple varieties.

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