Historical and Projected Changes in Chill Hours and Spring Freeze Risk in the Midwest United States

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Research Article

Keywords: chill hours, spring freeze, phenology specialty crops, CMIP6, Midwest

Posted Date: November 14th, 2023

DOI: https://doi.org/10.21203/rs.3.rs-3471509/v1

Abstract

In the United States Midwest region, the dormant or cold season has experienced significant change over the past several decades due to human-caused global warming, and changes are projected to continue or intensify through the end of the century. Realized and potential changes in crop chill hour accumulation and spring freeze injury risk are particularly concerning for specialty growers in the Midwest region, but relatively little work has been done to assess these changes and help guide producer management strategies accordingly. In this study, we use a combination of historical observations and CMIP6 multi-model ensemble projections to assess recent and projected changes in chill hour accumulation and spring freeze injury risk in the Midwest, using specific examples of apple and peach crops. We find chill hour accumulation has increased in much of the Midwest since 1950 and CMIP6 projections show continued increases through the next 70+ years. While the southern Midwest is projected to lose chill hours through late century, the rate of decrease likely does not necessitate a substantial shift to lower chill requirement fruit cultivars. All varieties of apples and peaches tested would still be chill hour suitable for all but the far southern Midwest by late century under even the highest emissions scenario. Model projections also show decreased spring freeze injury risk across the southern Midwest due to earlier last spring freeze dates and slightly later bloom dates. Most of the central and northern Midwest are projected to experience small or negligible changes in spring freeze injury risk due to roughly equivalent trends in spring freeze and bloom dates. We present an important assessment of climate change impacts on Midwest perennial cropping systems; however, more collaborative work is needed between scientists, practitioners, and providers to both assess the current and future specialty crop agriculture risks due to climate change and explore viable solutions to ensure a resilient and growing Midwest specialty crop industry in the face of changing climate, economic, and social systems.

1. Introduction

Climate change in the United States Midwest region is often associated with annual crop agriculture, particularly corn and soybean systems (Gordon *et al.* 2015; Church et al. 2018; Jin et al. 2018). However, the Midwest also has a thriving and diverse, multi-billion-dollar non-commodity specialty crop sector, including dozens of types of fruits, vegetables, nuts, and nursery crops, all of which are sensitive to the region's changing climate (Johnson and Wright Morton, 2015). Climate change impacts to perennial cropping systems in the Midwest are challenging to understand and communicate because they are sensitive to changes in growing season and dormant season weather conditions (Kistner *et al.* 2017; Han *et al.* 2021; Jones et al. 2022). Midwest cold season temperature and precipitation have significantly increased over the past several decades and are projected to continue to do so in the future (Demaria et al. 2016; Chin, 2018; Weiskopf *et al.* 2019; Ford *et al.* 2021; Wuebbles et al. 2021). One potential impact of increasing cold season temperatures are changes in chill hour accumulation that affect the timing and variability of critical phenological stages (Luedeling, 2012; Park et al. 2018; Martins et al. 2020; Bowling et al. 2020). Concurrent warming trends in spring, though, could result in a shift toward earlier last spring freeze dates in the Midwest (Abendrouth et al. 2019; Baum et al. 2020), thereby complicating the prognosis of spring freeze injury risk for perennial crops.

A commonly prescribed adaptation strategy for climate change in many global regions is to work with lower-chill requirement cultivars of popular crops (Parker and Abatzoglou, 2019; Pechan et al. 2023); however, this strategy may increase spring freeze injury risk in continental climates in which there is a lesser risk of not meeting high chill hour requirements (DeGaetano, 2018). Effective communication of climate change and potential shifting impact risks to agricultural systems are critical to ensure farmers can take effective adaptive and mitigative measures to reduce long-term exposure (Linder and Campbell-Arvai, 2021). Furthermore, presenting farmers and farmer advisors with long-term changes or shifts in agroclimatic metrics, such as chill hours, has been shown to increase farmer perception of the information's value for decision making (Jagannathan et al. 2023).

Given the need for useable climate change information for agricultural resilience, the significant change in Midwest cold season temperatures, and the economic and cultural importance of the Midwest specialty crop industry, the focus of this study is to use a combination of historical observations and model projections to estimate changes in chill hour accumulation and spring freeze risk in the Midwest. We use specific examples of apple and peach crops; however, much of this work is generalizable to many Midwest perennial cropping systems.

2. Data & Methods

2.1 Air Temperature

The study uses gridded daily maximum and minimum air temperature from NOAA's nClimGrid-Daily product (Durre et al. 2022) to calculate chill hour accumulation and spring growing degree days for historical analysis (1951–2021). The nClimGrid-Daily product is based on the Global Historical Climatology Network-Daily dataset, and it provides daily maximum and minimum temperature across the United States at an approximately 5 km horizontal resolution. The daily grids are the result of climatologically aided interpolation, incorporating morning and midnight observations and accounting for changes in station density, observation time, and other factors that affect the field homogeneity. More information for the methods and validation of the nClimGrid-Daily product can be found in Durre et al. (2022).

We use daily maximum and minimum air temperature output from the NASA Earth Exchange Global Daily Downscaled Projections (NEX-GDDP-CMIP6, Thrasher et al. 2022) to quantify future cold season temperature change and corresponding changes in chill hour accumulation and spring freeze risk. More details on the NEX-GDDP-CMIP6 dataset are in the Supplemental Material. Projected changes in chill hours are based on the difference between the historical period (1984–2014) and the future period (2036–2065 as Mid Century and 2071–2100 as Late Century). Projected changes are considered robust if at least 75% of models agree on the change sign.

2.2 Chill Hour Calculation

Methods for calculating chill hour accumulation are almost as numerous as their applications, and studies have shown increasing temperatures may affect the ability of some methods to properly represent changing chill hour accumulation (Luedeling et al. 2009; Darbyshire, 2011; Melke, 2015). To test the sensitivity of the results to the chill hour method, we repeated the historical analysis with three different methods: “Simple Method”, “Utah Method”, and “Dynamic Method”. Methodological details for each of these chill hour techniques are in the Supplemental Material. We use a spatially varying chill accumulation season that commences when a location begins to positively accumulate chill hours (e.g., Cesaraccio et al., 2004; DeGaetano, 2018). We begin calculating chill hours across the Midwest on August 1, and find the first 7-day period after August 1st over which the daily accumulation of chill hours is positive and begin accumulating chill hours from that date. This process is done separately for each individual grid cell across the region. The chill accumulation season at any grid cell ends at either peak chill accumulation or May 1st, whichever comes first.

We use the idealized temperature curve from Linvill (1990) to estimate an hourly temperature time series from nCLimGrid-Data and NEX-GDDP-CMIP6 daily maximum and minimum values. The Linvill (1990) method has been shown to well represent hourly temperature variability and compares well with actual hourly temperature observations (see Supplemental Material and Figure S1).

2.3 Sequential Model for Spring Freeze Risk

Chill hour accumulation is only one component of the risk of spring freeze injury to perennial crops. Spring freeze risk is also dependent on the air temperature following the fulfillment of the plant’s chill requirement and the likelihood of temperatures that can cause injury at various phenological stages. We use a sequential model following the methods of DeGaetano (2018) to predict apple phenology and corresponding spring freeze risk, using both historical and projected temperature data. More details on the sequential model are in the Supplemental Material.

We use a 31-year record of observed apple bloom dates to validate the bloom date estimates from the sequential model. Observed bloom dates from 1991 to 2022 were provided by a commercial grower in Union County, Illinois and contained a mix of apple varieties including McIntosh, Gala, and Fuji. The grower estimated their bloom date time series had an error range of 2–3 days. We hoped to complete a similar spring freeze risk analysis for one or more peach varieties; however, we were unable to procure peach bloom observations from the Midwest and therefore only assessed apple spring freeze risk.

3. Results

3.1 Chill Hour Climatology & Change Assessment

The observed (1951–2021) climatological season-total chill hours across the Midwest are broadly similar between the Simple, Utah, and Dynamic Methods (Fig. 1a), with spatial correlations between the three methods all exceeding 0.97. Season total chill hours are highest in the eastern half of the Midwest region where winter temperatures are moderated by the Great Lakes and heat transport from the Gulf of Mexico, relative to the western and northwest portions of the region. The highest totals tend to span around 43° to 36°N latitude, where winter temperatures are more frequently within the range deemed ideal by each of the three methods for chill accumulation. Areas farther south than 36°N experience milder winters with shorter overall periods of potential chill accumulation.

Historical (1951–2021) total season chill hour accumulation, assessed using a Theil-Sen median pairwise of slopes trend estimate (Sen, 1968), exhibits an increasing trend in the northern half of the Midwest but has no apparent trend in the southern half of the region (Fig. 1b). The total change over the 70-year historical period in the northern Midwest represents a 30–35% increase in total chill hour accumulation. Decreasing chill hour trends in relatively small areas of the southern Midwest are modest by comparison, on the order of -1 to -3 hours per year or 5–15% decreases since 1951. The consistency between the three chill models in both the climatological chill hour patterns and trends over the historical period gives some confidence that the results are less sensitive to the method by which chill hours are accumulated. The remaining chill hour analyses were done using only the Utah Method for simplicity and brevity.

We evaluate the frequency of meeting chill hour requirements for popular varieties of apples and peaches in the Midwest (Fig. 2). The Contender variety of peach has an estimated chill hour requirement of 1050 hours, and the Gala and Fuji varieties of apple have an estimated chill hour requirement of 800 hours. Both thresholds were the best estimate of chill requirements for each variety, based on Illinois Extension and Illinois apple and peach grower input. We split the historical period into two 30-year sections (1951–1980, 1991–2020) and calculate the number of years in each 30-year period in which the peach or apple chill accumulation threshold was reached by May 1st. We denote the area in which these thresholds were reached in at least 9 out of 10 years, presuming this is a reasonable level of risk assumed by peach and apple growers. Comparison of the maps shows the area that met peach and apple chill accumulation requirements in at least 9 out of 10 years expanded between the early and late historical periods (Fig. 2). In both cases of Contender peach and Gala and Fuji apple varieties, more of the northern Midwest met their respective accumulation thresholds between 1991 and 2020 than between 1951 and 1980.

Trends in October-April average daily minimum temperature between 1951 and 2021 show extensive warming across the Midwest (Figure S2), consistent with Angel et al. (2018) and Ford *et al.* (2021). We see a much larger magnitude warming trend in the 10th percentile of October-April daily minimum temperatures, relative to the median and 90th percentile values. Practically, this means the very lowest cold-season temperatures are warming faster than moderately low temperatures, indicating a distribution change rather than a shift toward higher temperatures overall. The disproportionate warming of the left (i.e., cold) tail of the cold season temperature distribution increases the frequency of temperature hours that are within the ideal chill accumulation range in the northern Midwest, where historically more hourly temperatures fell outside that range. Warming has therefore increased frequency of chill hours on cold season days in the northern Midwest and increased the frequency of the number of days in which chill hours accumulate (Figure S2). The same warming pattern in the southern Midwest also increases or causes negligible change in the frequency of chill hours, but effectively shortens the length of the season over which chill hours are accumulated (Figure S2). A region-wide climate change forcing results in different impacts to chill hour accumulation due to the climatological differences in winter weather across the Midwest.

3.2 Chill Hour Projections

The multi-model ensemble mean of season-total chill hour accumulation has a similar spatial pattern as the observations, with relative maxima in the eastern and central Midwest and relative minima in the far southern and northwest Midwest (Figure S3). More CMIP6 ensemble comparison details are in the Supplemental Material. As much as can be inferred from model performance during the historical period, we are confident using the entire 24-model ensemble to assess potential future changes in Midwest chill hour accumulation.

The CMIP6 multi-model ensemble mean shows projected increases in total chill hour accumulation in the northern Midwest and decreases in the southern Midwest by mid- and late-century (Fig. 3). The magnitude of projected changes is sensitive to SSPs, with larger magnitude change projected under higher emissions pathways. For example, chill hours are projected to increase on average by 100 to 400 hours in the northern Midwest and decrease by the same magnitude in the southern Midwest by late century under SSP 245, compared to projected changes between 300 and 600 chill hours in the northern and southern parts of the region under SSP 585. At least 75% of the CMIP6 models agree on the sign of the projected change throughout most of the northern and southern parts of the region, indicated by hatching in Fig. 3.

Ensemble mean projections also show increased annual chill hour accumulation variability in the northern Midwest, relative to historical (Supplemental Figure S3); however, variability is projected to not substantially change or decrease in much of the southern and eastern Midwest. We select a southern sub-region and a northern sub-region (Supplemental Figure S4) to contrast the projected change in daily chill accumulation and show the SSP 245 late century projections against the model historical simulations (Fig. 4). Projected continued increases in cold season temperatures of roughly the same magnitude in the Midwest is expected to result in fewer temperature hours in the ideal range for chill hour accumulation in the southern Midwest, causing reductions in both (1) the length of the period over which chill hours accumulate and (2) the number of chill hours accumulating each day during the cold season. The SSP 245 late century projections show chill hour reductions in the southern region across the entire cold season; however, the largest decreases relative to the historical period are in the late fall and early spring.

While projections indicate an overall chill hour decrease in the southern region, the daily chill hour distribution is not expected to change substantially. In contrast, SSP 245 late century projections show a large change in both the season total chill hours and the distribution shape of daily chill hours in the northern region (Fig. 4). Chill accumulation in the northern region in the historical period occurred primarily before mid-December and after mid-February, because this is the period with the highest frequency of temperature hours in the ideal range for chill accumulation. However, projected warming throughout the cold season in the northern region results in a decrease in daily chill hour accumulation in September and October, followed by a substantial increase between November and March, and another decrease in April and May. The culmination of these projected changes leads to an overall larger season chill hour total, but with different daily accumulation characteristics. The bi-modal distribution of daily chill hour accumulation in the historical period is projected to shift closer to a unimodal distribution as daily chill accumulation in the middle of the cold season is projected to increase.

Changes in interannual variability of daily chill accumulation in the northern sub-region are also evident in the late century projections, relative to historical (Figure S5). The consequences of the change in variability are an increase in mean daily accumulation and mean season total accumulation, but with significantly higher interannual variability. Practically, higher chill hour accumulation in the northern Midwest by late century could be conducive to perennial crops with higher chill requirements, such as certain cultivars of peaches that are currently grown in the southern Midwest. However, the concurrent projected increase in interannual chill hour variability is an important source of uncertainty for new crop suitability to the northern Midwest and could result in an untenable frequency of years in which crop chill requirements remain unmet by the end of the dormancy season.

We assess the frequency with which the chill hour requirements of specific cultivars of peach and apple are met by May 1st across the Midwest in the historical, mid century, and late century model periods. The first day meeting the 1050 chill hour requirement of Contender peaches ranges from mid-March in the southern Midwest to mid-May in the northern Midwest (Fig. 5a). Contender peach chill requirements are projected to be met 3 to 6 weeks earlier in the northern Midwest and 2 to 4 weeks earlier in the central Midwest by mid and late Century, irrespective of the SSP. Meanwhile, the first day meeting the chill hour requirement is not projected to change noticeably or even delay by up to 2 to 4 weeks across the far southern Midwest.

The result of projected changes in total chill hour accumulation is a northward shift in the area meeting Contender peach chill requirements in at least 9 out of 10 years, relative to historical (Fig. 5b). The northwest part of the Midwest only met Contender Peach chill requirements in 10 to 50% of years in the historical period, compared to 70 to 100% of years in the projected periods. The far southern Midwest – a region meeting the Contender Peach chill hour requirement in at least 90% of years in the historical period – is projected to meet chill hour requirements in 50 to 75% of years. We found a similar projected northward expansion of chill hour suitability for Gala Apple (Supplemental Figure S6); however, the relatively lower Gala chill hour requirement reduced the area of the southern Midwest that is projected to no longer meet those requirements in at least 90% of years. Not meeting requisite chill hour totals can result in poor flower set, fruit quality, and overall lower fruit yields (Oukabli et al. 2003; El-Yazal, 2019). Therefore, the projected increase in cold season temperatures across the Midwest results in a potential increased chill hour suitability in the northern Midwest for certain perennial crops like peaches, but with a potential decreased chill hour suitability for the same crops in the southern Midwest.

3.3 Apple Spring Freeze Risk Projections

To better understand the cumulative impacts of potential changes in cold season temperatures on spring freeze risk, we use a sequential model to predict apple phenology with both historical and projected temperatures. We selected Gala and Fuji apple cultivars, each with a chill requirement of 800 hours. The sequential model was tested using hourly temperatures from nClimGrid-Daily to estimate the first date of apple full bloom and was validated with a record of observed apple bloom dates from 1991–2022. The observed bloom dates were provided by a commercial grower in Union County, Illinois and contained a mix of apple varieties including McIntosh, Gala, and Fuji. The sequential model performed very well compared to the bloom observations, with an R^2 of 0.83 and an average error of 1.03 days (Supplemental Figure S7). We use − 3.9°C as a threshold to determine the risk of spring freeze damage for Gala and Fuji apple varieties, the temperature at which 90% kill occurs in most apple varieties (Michigan State University Extension, 2014).

The sequential model was applied to the 71-year observed temperature record to establish an apple bloom date climatology for the Midwest region (Supplemental Figure S8). The average estimated full bloom date ranges from mid-March to early May, with an interannual variability of 4 to 10 days. The last spring freeze dates exhibit larger interannual variability than apple bloom dates, on the order of 6 to 20 days, with the largest variability in the southern Midwest. The historical observed average apple full bloom date occurs 5 to 30 days after the observed average last spring freeze date across the Midwest, with the smallest differences, and therefore highest freeze damage risk, in the southern and western Midwest (Fig. 6). We express the overall spring freeze injury risk as the percent of years (out of 71) that have an apple bloom date falling on or before the last spring freeze date. Higher spring freeze damage risk in the southern Midwest is due to larger and quicker accumulation of chill hours prior to March 1, relative to the northern Midwest, despite an overall earlier last spring freeze date.

The sequential model was applied to CMIP6 model ensemble simulations to assess the effects of projected increasing winter and spring temperatures and changes in temperature variability. Projected increases in chill hours and early spring temperatures cause earlier apple full bloom dates across most of the region by mid and late century under both scenarios (Fig. 7a). The average date of apple bloom in the northern two-thirds of the Midwest is projected to trend 5 to 25 days earlier by mid century, and 10 to 35 days earlier by late century. At least 75% of the CMIP6 models agree on the sign of change in virtually all the area with a projected decreasing bloom date trend. Only the very southern edge of the Midwest region shows an average projected delay in apple full bloom dates, with magnitudes ranging from 5 to 25 days later (Fig. 7a). However, fewer than 75% of the CMIP6 models agree on the sign of projected bloom date changes in much of the southern Midwest, suggesting that while apple full bloom is expected to occur earlier than the present under continued warming in the central and northern Midwest, a similar change in cold season temperatures does not elicit a consistent apple bloom trend in the southern Midwest. Meanwhile, the date of last spring (-3.9°C) freeze is also projected to trend earlier in the spring across the region (Fig. 7b).

We use the projected changes in apple full bloom dates and last spring freeze dates to assess the potential change in spring freeze injury risk. A model year is considered to have a risk of freeze injury if the estimated bloom date falls on or before the last spring freeze date. We calculate the overall risk of freeze injury for each model, scenario, and future period as the percentage of years (out of 30) that meet those freeze injury potential criteria. The maps in Fig. 7c show the multi-model ensemble averages of these projected risk changes. Projected trends in apple bloom and last spring freeze dates combine to make an inconsistent pattern of projected changes in the risk of spring freeze injury (Fig. 7c). The southern Midwest is projected to experience, on average, either no change or later apple bloom dates and earlier last spring freeze dates, resulting in a considerable decrease in spring freeze injury risk by mid and late century. Most of the southern quarter of the region is projected to experience between 2 and 10 fewer years (out of 30) with a potential spring freeze injury risk to apples, with over 75% of CMIP6 models agreeing on the sign of the change. In contrast, most of the northern three-quarters of the region is projected to experience either a slight decrease or slight increase (± 5 years out of 30) in spring freeze risk. The lack of strong spring freeze injury risk trends in much of the Midwest is due to similar magnitude projected changes in bloom date and last spring freeze dates, which essentially results in a shift in the current spring phenology season but does not appreciably change the risk of spring freeze injury.

In contrast, much of Ohio and eastern Kentucky are projected to experience a large increase in spring freeze injury risk by mid and late century, which results in projected decreasing apple bloom date trends and negligible projected trends in last spring freeze dates. This combination moves apple bloom dates closer to the climatological average last spring freeze date and increases spring freeze injury risk relative to historical. While at least 75% of the models agree on the projected earlier apple bloom date trends in this part of the Midwest, they do not agree on projected changes in last spring freeze dates. Therefore, the strong spring freeze injury risk trends in the eastern Midwest should be viewed carefully in the context of large model uncertainty of changes in last spring freeze dates in that part of the region.

3.4 Projected Changes in Interannual Variability

The average condition of chill hours, spring phenology, and spring freeze risk are informative for understanding climate change impacts on perennial crop agriculture in the Midwest; however, cold season temperature interannual variability is equally important for crop management. We represent the interannual variability of projected apple bloom dates and last spring freeze dates for each model, scenario, and future period as the standard deviation over each 30-year period. These estimates of variability are then compared to the same calculation over each model’s historical period, and the difference between the projected and historical variability values are shown in Figure S9. Interannual variability in apple bloom dates are projected to increase by 5 to 15 days across the far southern Midwest under both scenarios and both periods (Figure S9). Interannual variability in the last spring freeze date is also expected to increase in the future (Figure S9). The largest projected increases of 5 to 15 days are in the central and eastern part of the region and are larger in the SSP585 late century simulations. Expectations of when the last spring freeze will occur are important for producer decisions of when spring activities are completed. Therefore, increased interannual variability in both bloom dates and spring freeze dates could create additional challenges for crop management because many decisions, including timing of thinning, pest and weed management, and pollination, are determined in winter or very early spring, ahead of bloom.

4. Discussion

4.1 Perennial Crop Implications of Warmer Midwest Winters

The Midwestern US region has exhibited a pronounced cold season warming trend that is directly attributable to anthropogenic global warming, and models show consistent projections of continued warming trends through the end of the century (Angel et al. 2018; Wuebbles et al. 2021). However, the sectoral impacts of winter warming in the Midwest are more complicated and non-linear than a relatively simple increasing temperature trend would imply (Wu et al. 2018; Weiskopf *et al.* 2019; Byun et al. 2019; Scott et al. 2021). The climatological diversity of the Midwest region, which is magnified in the winter, complicates a region-wide prognosis of what economic, environmental, and social impacts have been or could be caused by warmer winters.

Higher region-wide cold season temperatures have resulted in significant increases in chill hour accumulation in the northern Midwest by increasing the frequency of hours during which temperatures are within an ideal range for plant chill accumulation. While similar cold season temperature trends in the southern Midwest have caused an increase in daily average chill hour totals, they have also reduced the number of days in fall and spring in which chill hours are accumulated, resulting in no overall chill hour trends in the southern Midwest. The contrast between the Midwest subregions are consistent with recent assessments in both temperate and colder, continental climates (Houston *et al.* 2018; Parker and Abatzoglou, 2019; El Yaacoubi et al. 2020, DeGaetano, 2018; Fraga et al. 2019).

Models consistently project increasing chill hour totals in the northern Midwest, caused by large increases in daily accumulation between December and February, relative to the historical period. Meanwhile, projected continued warming in the southern Midwest results in substantial decreasing chill hour totals by mid and late century under both SSPs. The projected lower chill hour climatology in the southern Midwest results in a decrease in the number of years in which peach chill requirements are met, potentially resulting in lower peach crop suitability in this part of the region where peaches are currently grown. Similar concerns of future peach suitability have been noted in the southeast US due to winter warming trends (Carbone and Schwarts, 1993; Parker and Abatzoglou, 2019). The southern extent of chill hour suitability of Gala and Fuji apple varieties were unaffected by projected decreases in southern Midwest chill hour accumulation. However, the northern extent of both apple and peach crop chill hour suitability is projected to migrate northward in the region because of increasing total chill hour trends in the northern Midwest.

The risk of spring freeze injury following dormancy break is a critical factor for crop suitability and viability. Our assessment of future spring freeze injury risk also produces mixed results. The date of the last potentially damaging spring freeze (-3.7°C) is largely projected to occur earlier in the spring, implying a potentially reduced risk of spring freeze injury. However, as with chill hour accumulation, there are considerable differences in projected changes in the timing of phenological stages across the Midwest. Projected decreasing chill hour accumulation in the southern Midwest is expected to delay fulfillment of apple chill requirements, thereby delaying dormancy break and subsequent bud and bloom stages. The combination of earlier last spring freeze dates and later full bloom dates result in decreased apple freeze injury risk in the southern Midwest. In contrast, projected quicker chill hour accumulation results in an earlier fulfilment of apple chill requirements in the northern and central Midwest, accelerating dormancy break and subsequent bud and bloom stages earlier in the spring. For most of the central and northern Midwest, the combination of earlier last spring freeze dates and earlier apple bloom dates results in small or negligible changes in spring freeze injury risk by mid and late century. The exception to these patterns is the far eastern Midwest, with ensemble mean projections of large increases in spring freeze injury risk, but with large model uncertainty.

Interannual variability of cold season temperatures impacts chill hour accumulation and spring freeze injury risk (Luedeling et al. 2013; Benmoussa et al. 2017; DeGaetano, 2018; Zhang et al. 2021). Practically, large variability around a mean condition of winter or spring climate can create a more challenging environment for viable fruit production because of uncertainty in the timing of decisions for crop management such as chemical thinning, nutrient application, weed and pest management, and employment considerations like work visas. The southern Midwest is projected to experience large interannual variability in projected apple bloom dates. While the CMIP6 ensemble average indicates decreased spring freeze injury risk in the southern Midwest, model uncertainty is high with variability in projected risk changes between models exceeding the ensemble mean risk.

4.2 Working Toward a Climate-Resilient Midwest Specialty Crop Sector

Much research has been devoted to the measured or potential changes in weather hazards related to long-term winter warming trends in the Midwest, and consequential impacts to infrastructure (Reynolds et al. 2020), ecology (Swanston et al. 2018), and public health (Anenberg et al. 2017). Likewise, climate change assessments for Midwest agriculture often focus on commodity or row crop systems that comprise most Midwest working lands (e.g., Hatfield *et al.* 2012; Abendrouth et al. 2021). Relatively less work has been done to assess the current and projected impacts of cold season climate change to the important Midwest specialty crop sector, despite the demonstrated impacts of extreme weather conditions on specialty crops in the region (Kistner *et al.* 2017; Ortiz-Bobea et al. 2018; Kral-O'Brien et al. 2019; Haigh et al. 2022) and the recognition of climate change as an important factor for producer decision making (Johnson and Morton, 2015). Ensuring the Midwest can continue and grow fruit and vegetable production despite climate change requires developing effective collaboration and communication between researchers, advisors, and producers.

Our study of cold season temperature impacts to perennial crops is an important but incomplete assessment of Midwest specialty crop resilience. More work is needed to develop crop-specific measures of responses, tolerances, and risk to climate change, and to provide producers and crop advisors with actionable projections that target on-farm decision making. Haigh et al. (2022) developed a framework for this kind of co-production of knowledge for specialty crop drought resilience in the Midwest, which could be adapted for broader discussions of climate change. Additionally, the complex impacts of changing warm and cold season conditions on insect pests, diseases, weeds, and overall integrated pest management is a critical area of future research (Bale and Hayward, 2010). Clear communication between scientists, practitioners, and producers is key to ensuring research is useable for developing systemic resilience to climate change issues, and that includes clear and relevant communication about uncertainty. The continued development of research and solutions on climate change impacts to specialty crops in the Midwest – and funding for such work – is particularly critical considering current and projected global social, environmental, and economic issues including food insecurity, water quality problems, and volatile markets (Prokopy et al. 2020).

Our study has multiple, important limitations, the first of which is uncertainty in crop-specific chill requirements, temperature tolerances, and relationships between spring environmental conditions and phenological development. Thresholds, such as the 800 chill hour requirement of Gala and Fuji apple varieties, are estimates based on limited field experiments and producer and horticultural expertise. However, plants' responses to environmental conditions like cold season temperatures will vary depending on myriad of factors including their specific location and overall health. Consequently, the performance of chill hour accumulation models and spring phenology models will vary depending on these and other factors, which partly contributes to the significant disparity between studies in what models work best in specific locations (e.g., Luedeling and Brown, 2011; Measham et al. 2014). Additionally, we only examine spring freeze injury risk with respect to the full bloom; however, injury can occur well before that phenological stage (DeGaetano, 2018). Therefore, our projections of injury risk should be interpreted as only one aspect of the overall risk of spring freeze damage to specialty crops. Lastly, crop suitability is dependent on many more factors than chill hour accumulation and spring freeze injury risk (Seifert and Lobell, 2015; Chemura et al. 2020; Appelt et al. 2023). Therefore, prescriptions of what crops could be grown in the Midwest or any global region should consider more than these two factors.

5. Conclusion

We use a combination of historical observations and CMIP6 multi-model ensemble projections to assess recent and potential future changes in chill hour accumulation and spring freeze injury risk for perennial crops in the Midwest United States. Overall, observations indicate increased chill hour accumulation in much of the Midwest over the past 70 years and CMIP6 projections of continued increases through the next 70 + years. The southern Midwest is expected to lose chill hours, but not at a rate that would require a substantial shift to very low chill requirement fruit cultivars (e.g., Bowling et al. 2020). Both varieties of apples and the variety of peach tested would still be chill hour suitable for all but the far southern

Midwest by late century even under the high emissions scenario. The largest observed and projected increases in chill totals in the northern Midwest are accompanied by the largest projected increases in interannual variability. Therefore, while the climatological average chill hour totals in the far northern Midwest projected by mid or late century could support some of the higher chill requirement cultivars of apples or peaches, increased year-to-year variability could create additional management challenges for producers in this region.

We use a sequential model to predict the timing of full bloom for Gala and Fuji apple varieties using historical observations and model projections and compare the estimated bloom dates to the dates of last potentially damaging spring freeze across the region. The CMIP6 model ensemble shows projected decreased spring freeze injury risk across the southern Midwest due to projected earlier last spring freeze dates and later apple full bloom dates. Most of the central and northern Midwest are projected to experience small or negligible changes in spring freeze injury risk due to roughly equivalent last spring freeze and apple bloom date trends earlier in the spring.

It is important to note that projections of crop-specific metrics such as chill hours, bloom dates, and spring freeze injury risk are based on temperature projections and thresholds that all bring various sources of uncertainty. Therefore, the results should be viewed as providing a broad perspective of observed and potential future changes in Midwest cold season climate and implications for perennial crops. Crop suitability is a complex function of (warm and cold season) climate, soils, markets, and management strategies, and our study only addresses part of these factors. This study provides an assessment of an important aspect of climate change impacts to specialty crops in an understudied region of the United States for non-commodity agriculture. More collaborative work is needed between scientists, practitioners, and providers to (1) assess the current and future specialty crop agriculture risks from climate change in the Midwest and (2) explore viable solutions to ensure a resilient specialty crop industry in the face of changing climate, economic, and social systems.

Declarations

Acknowledgements

Thank you to Parker Flamm at Flamm Orchards for apple bloom date data contributions (and for their delicious apples), both of which were a tremendous help for the project. The authors declare they have no financial interests.

Ethics Approval and Consent to Participate

Not Applicable

Consent for Publication

Not Applicable

Competing Interests

Not Applicable

Author Contributions

Trent Ford: conceptualization, methodology, validation, formal analysis, investigation, data curation, writing (original), visualization, project administration, funding acquisition

Liang Chen: methodology, software, formal analysis, investigation, writing (original), visualization, funding acquisition

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Dennis Todey: resources, writing (editing), supervision, funding acquisition

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Funding

This work was supported by the United States Department of Agriculture (ARS award 59-5030-2-003).

Data Availability

Historical and projected daily chill hour estimates from nClimDiv-Daily and NEX-GDDP-CMIP6 used in this study are made available via GitHub: https://github.com/IL-SCO/ChillHour.git

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Figures

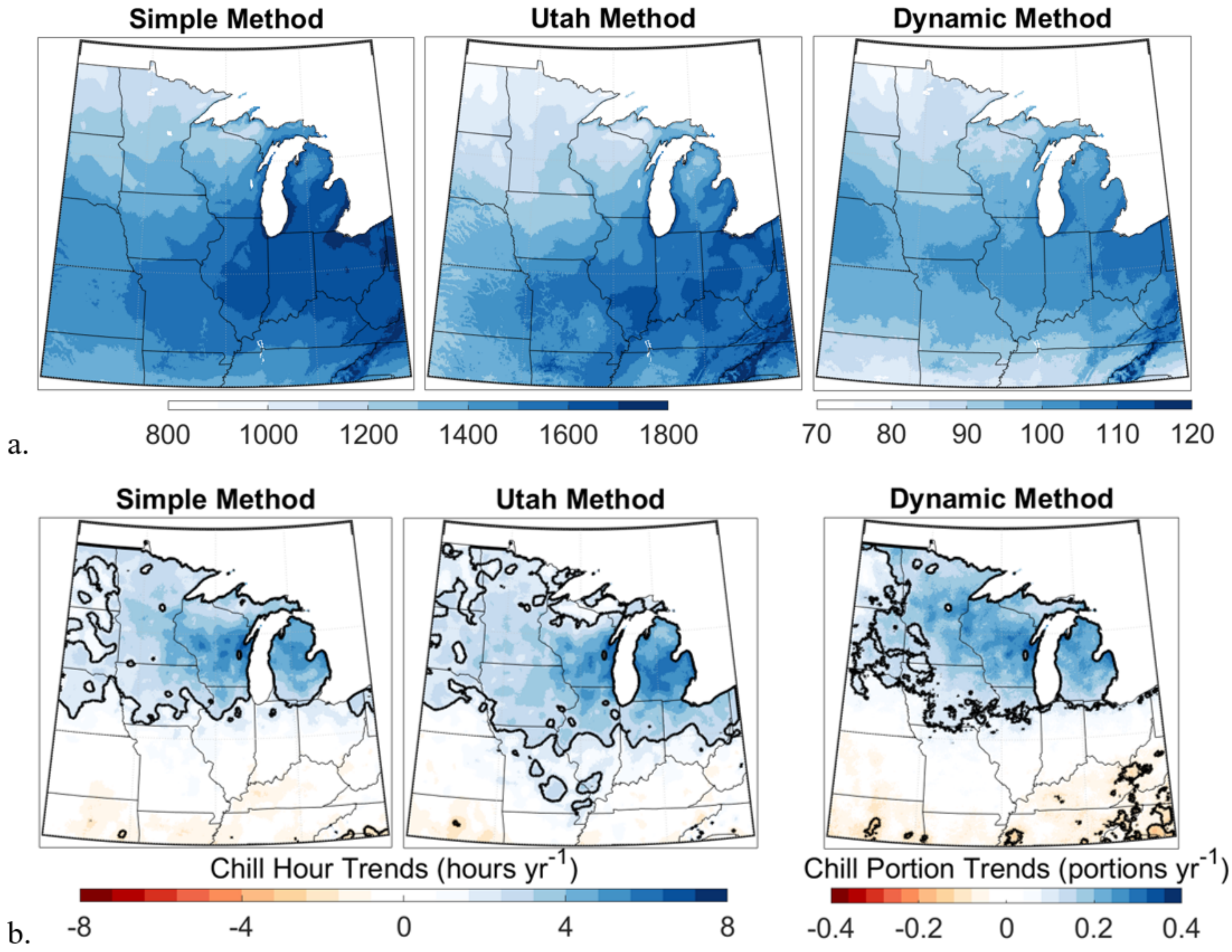

Figure 1

(a) Average season-total chill hour accumulation between 1951 and 2021. (b) Trends in total-season chill hours from 1951 to 2021. Chill hours were accumulated using the Simple Method, Utah Method, and Dynamic Method. The black contour in trend maps indicate statistical significance (p-value > 0.95).

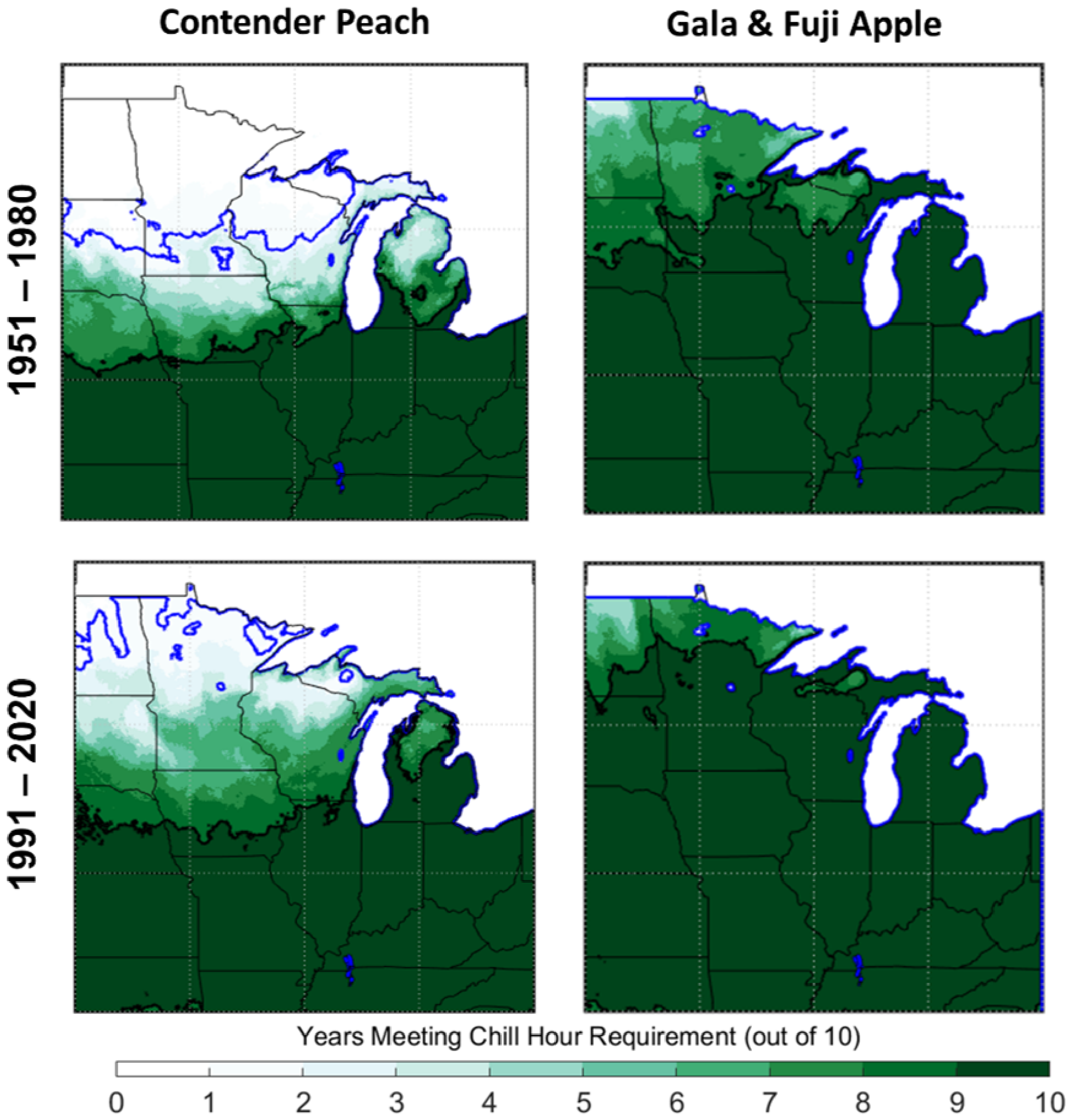

Figure 2

Maps show the number of years (out of 10) meeting the chill accumulation requirement of (left) contender peach and (right) Gala and Fuji apple varieties. The black contour denotes areas meeting the thresholds in at least 9 of 10 years and the pink contour denotes areas meeting the thresholds in at least 1 of 10 years. Frequencies are separated between the periods (top) 1951-1980 and (bottom) 1991-2020.

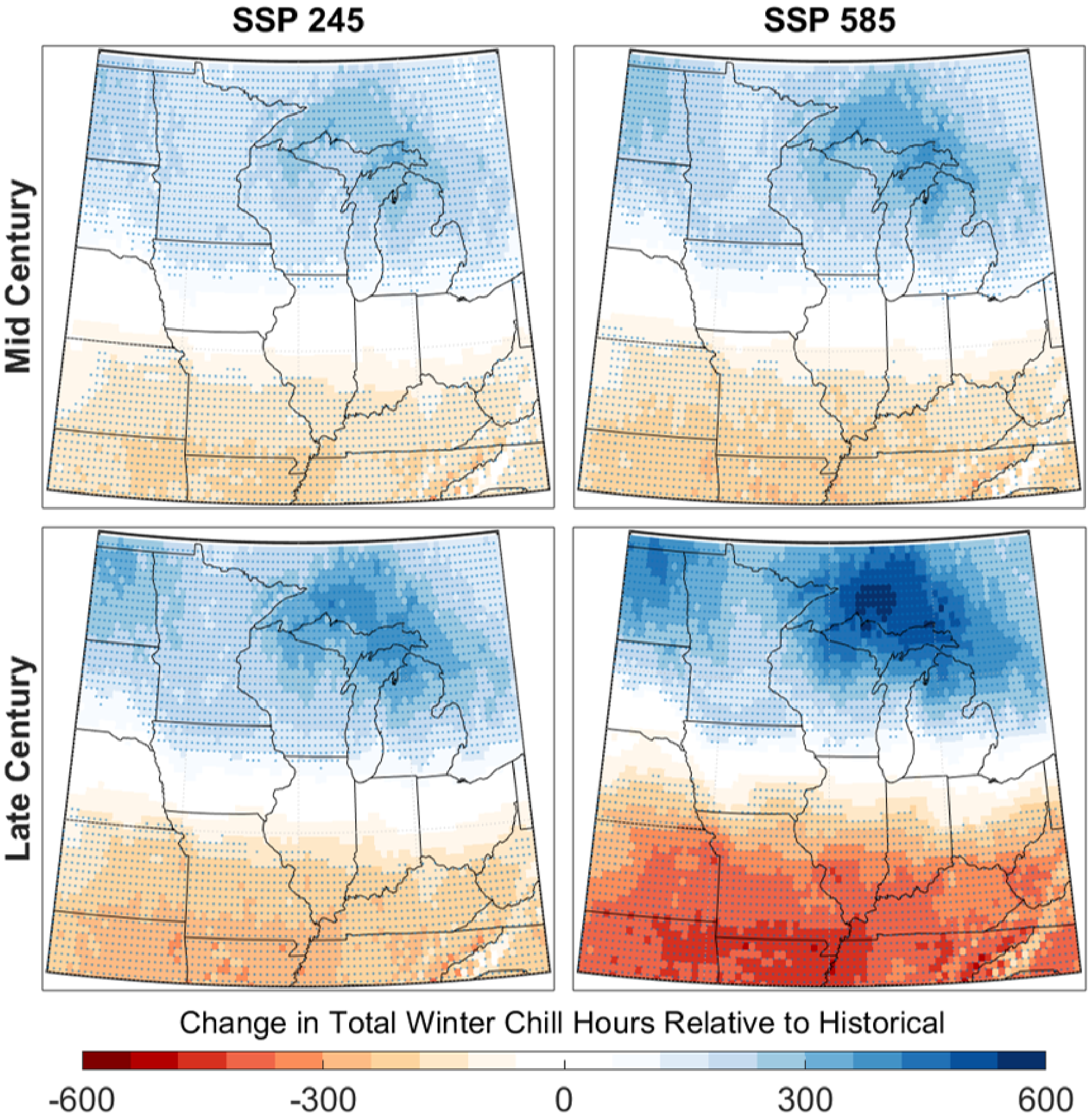

Figure 3

Maps show CMIP6 ensemble mean projected changes in total season chill hour accumulation, relative to the model historical period average. The panels show projected changes by mid and late century and under moderate and high emissions pathways. Stippling denotes areas where at least 75% of the models agree on the sign of the change.

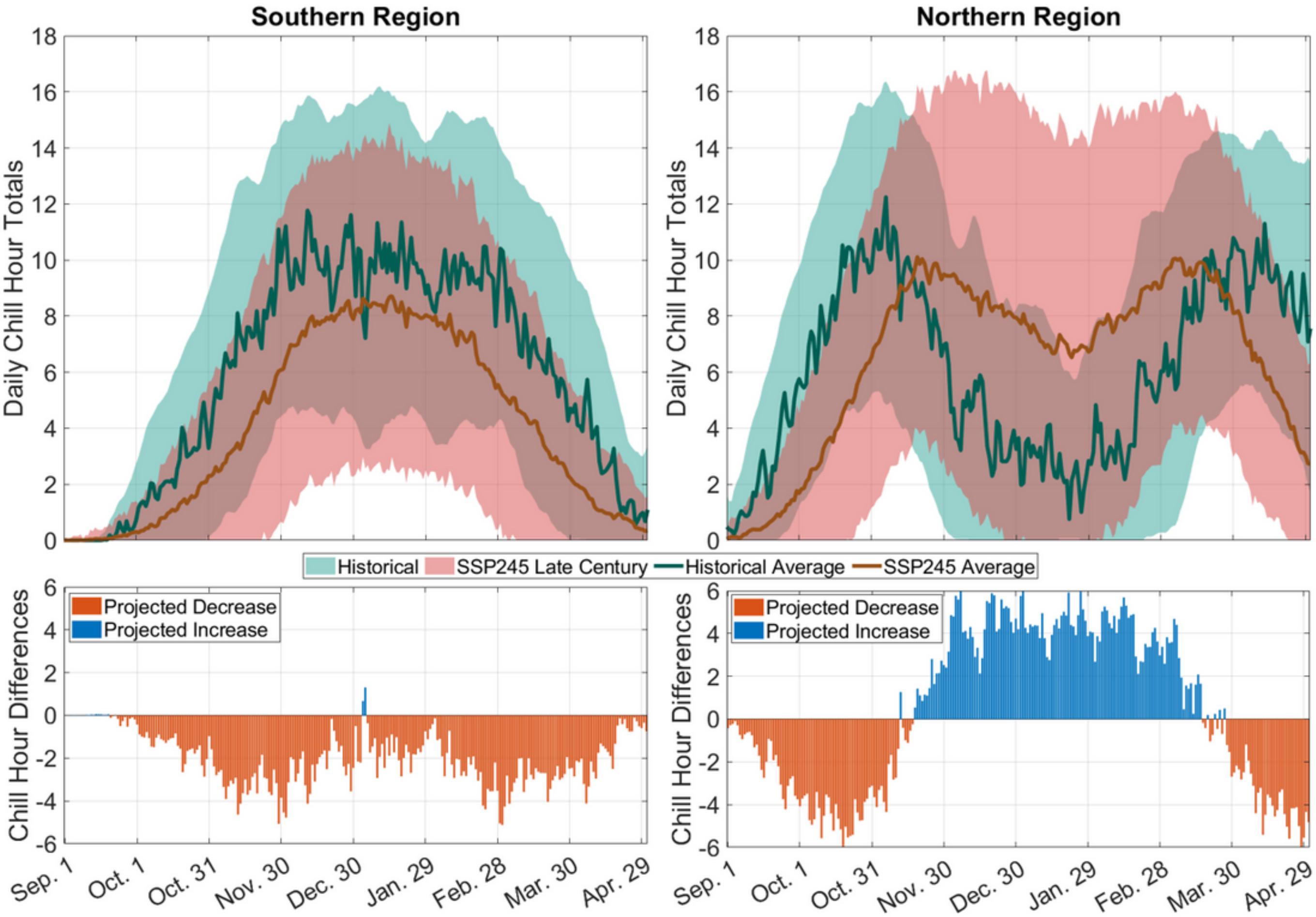

Figure 4

Comparison of daily chill hour accumulation between September 1 and May 1 in sub-regions in the southern and northern Midwest. Top panels show the distributions of model ensemble mean daily chill hour accumulation in each of the 30 years in the (green) historical and (red) SSP245 late century projected simulations, and the dark green and red lines show the 30-year means, respectively. The bottom panels show the daily chill hour differences between SSP245 late century projected and historical simulations for each day between September 1 and May 1. Red (blue) bars indicate a projected decrease (increase) in daily chill hour accumulation.

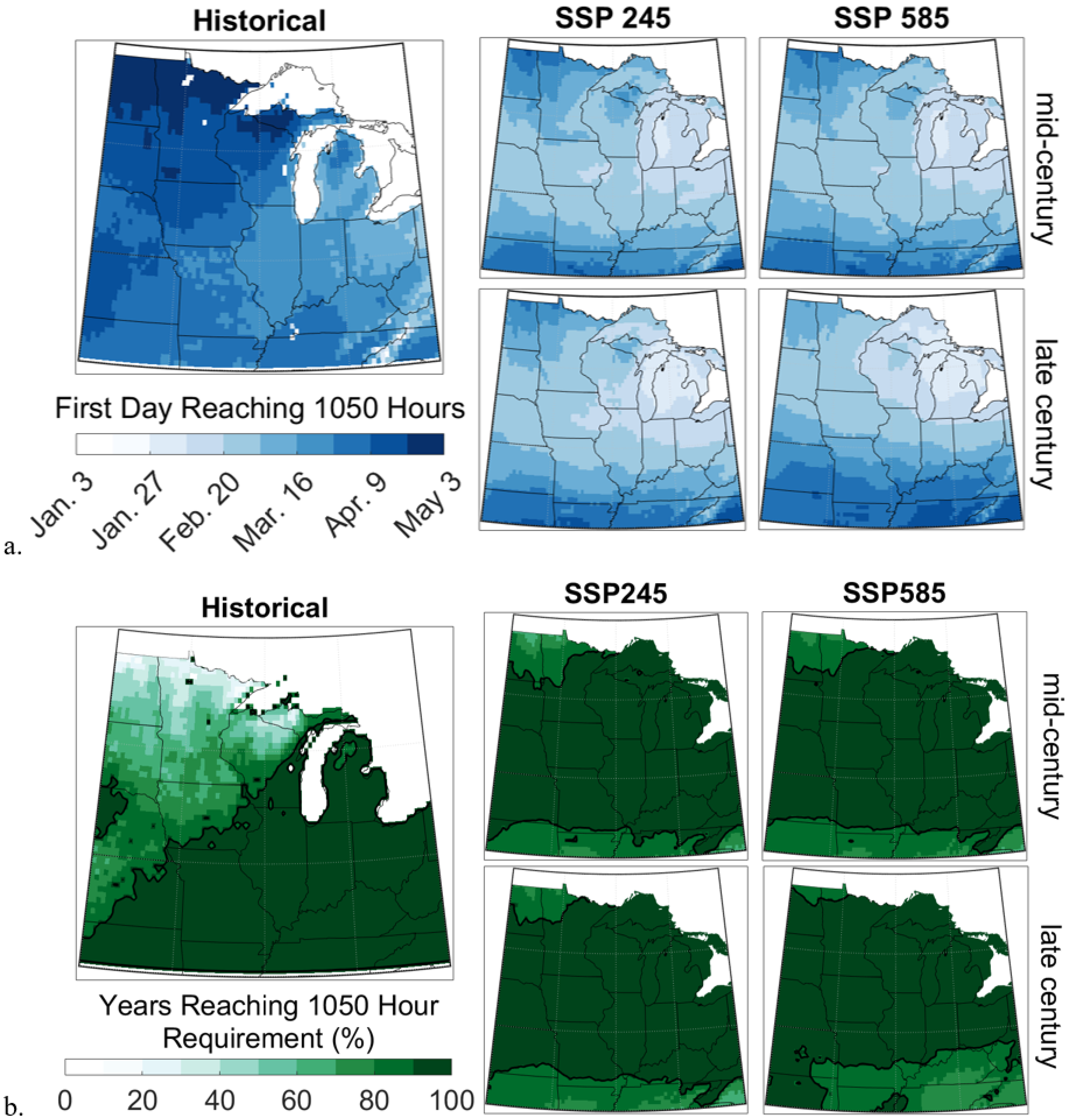

Figure 5

Maps in panel (a) show the historical and projected first day reaching the Contender Peach requirement of 1050 chill hours. Maps show the 30-year average over the historical period and projected periods by mid- and late-century under SSP245 and SSP585 pathways. Maps in panel (b) show the historical and projected percent of years in the 30-year historical and projected periods that meet the Contender Peach requirement of 1050 chill hours by May 1st. The black contour denotes areas meeting that requirement in at least 90% of years.

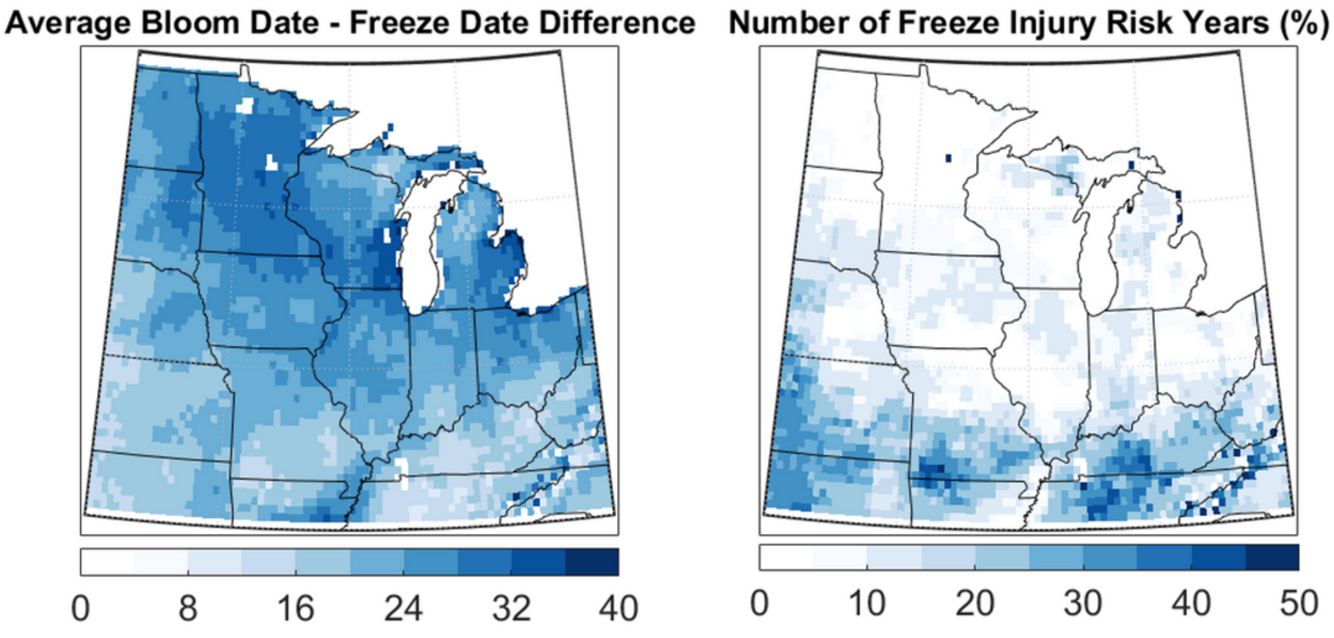

Figure 6

Maps show (left) the average difference between the estimated apple full bloom date and the last spring freeze date between 1951 and 2021, and (right) the percent of years over that historical period in which the full bloom date occurred on or before the last spring freeze date.

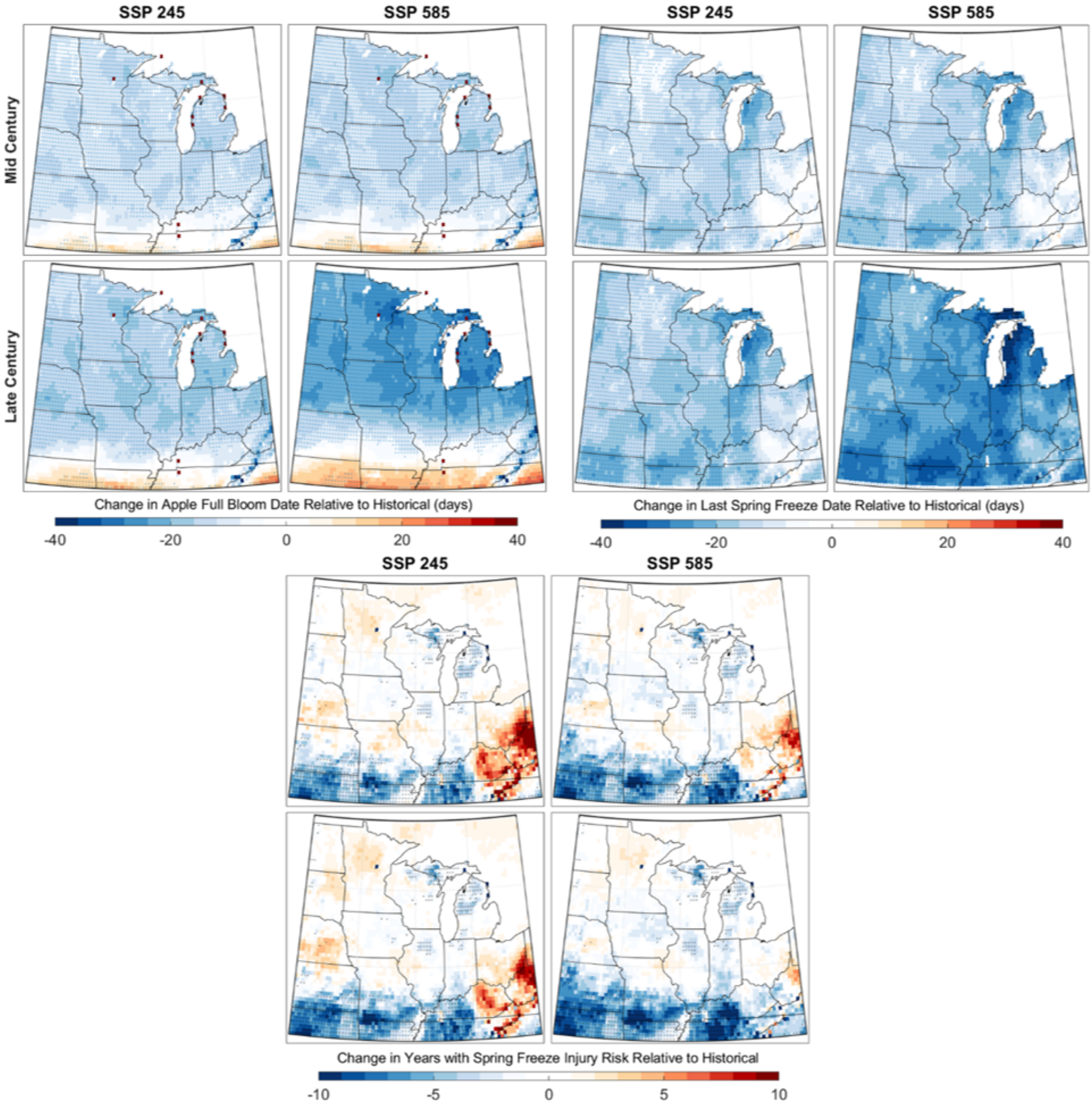

Figure 7

Top maps show projected changes in (left) apple full bloom date and (right) last spring freeze date relative to historical for moderate and high emissions scenarios by mid and late century. Bottom maps show the change in the number of years (out of 30) with a potential spring freeze injury risk for apple, relative to the historical. Stippling denotes areas where at least ¾ of the models agree on the sign of the change.

Supplementary Files

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