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LETTER

Changing climate risks for high-value tree fruit production across the United States

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Supplementary material for this article is available online

Abstract

Climate change poses growing risks to global agriculture including perennial tree fruit such as apples that hold important nutritional, cultural, and economic value. This study quantifies historical trends in climate metrics affecting apple growth, production, and quality, which remain understudied. Utilizing the high-resolution gridMET dataset, we analyzed trends (1979–2022) in several key metrics across the U.S.—cold degree days, chill portions, last day of spring frost, growing degree days (GDD), extreme heat days (daily maximum temperature >34 °C), and warm nights (daily minimum temperatures >15 °C). We found significant trends across large parts of the U.S. in all metrics, with the spatial patterns consistent with pronounced warming across the western states in summer and winter. Yakima County, WA, Kent County, MI, Wayne County, NY—leading apple-producers—showed significant decreasing trends in cold degree days and increasing trends in GDD and warm fall nights. Yakima county, with over 48 870 acres of apple orchards, showed significant changes in five of the six metrics—earlier last day of spring frost, fewer cold degree days, increasing GDD over the overall growth period, and more extreme heat days and warm nights. These trends could negatively affect apple production by reducing the dormancy period, altering bloom timing, increasing sunburn risk, and diminishing apple appearance and quality. Large parts of the U.S. experience detrimental trends in multiple metrics simultaneously that indicate the potential for compounding negative impacts on the production and quality of apples and other tree fruit, emphasizing the need for developing and adopting adaptation strategies.

1. Introduction

Climate variability and change are already affecting agricultural production across the United States (U.S.) and other nations around the world, with the burden of impacts falling disproportionately on farmworkers, low-income households, and rural communities (Brinkman *et al* 2016, Kerr *et al* 2022, Raj *et al* 2022). Projected climate change could exacerbate food insecurity among many communities in the absence of adaptation (Mbow *et al* 2020, Kerr *et al* 2022, Rezaei *et al* 2023). The production and yields of major U.S. commodity crops such as corn and soybean are being adversely impacted by changing climate conditions and these impacts are projected to worsen with additional global warming (Malcolm *et al* 2012, Gowda *et al* 2018, Pathak *et al* 2018, Jägermeyr *et al* 2021, Yu *et al* 2021, Sharma *et al* 2022, Bolster *et al* 2023). While the impacts of climate change on such crops have been widely studied, the impacts on specialty crops, like tree fruit, are less clear (Manners and van Etten 2018, Alae-Carew *et al* 2020, Leisner 2020, Kerr *et al* 2022).

Tree fruit crops have important benefits for food and nutritional security and the economy. Recent weather and climate extremes in the U.S. have had

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substantial impacts on these crops. For example, in 2017, the state of Georgia lost 70% of its total peach production due to a lack of chilling accumulation hours and a late spring freeze (Parker and Abatzoglou 2019). The record-breaking 2021 Northwest heat-wave in the U.S., damaged and reduced yields of several crops across the Northwest (White *et al* 2023). This includes a loss of 2.4% in apple production in Washington state—the leading U.S. producer of apples (USDA NASS CoA 2022), losses of 60%–70% for red raspberries, 70%–80% for black raspberries, 50%–100% for blackberries in the Willamette Valley in Oregon, and nearly 100% loss of blueberries on several farms in the Northwest (Bell 2021).

According to the U.S. Department of Agriculture (USDA), the U.S. is the third largest producer and exporter of apples in the world. In the U.S., apples are the most consumed fruit, and the industry generates nearly $3.1 billion in farm revenue (USDA NASS CoA 2022). Changing climate conditions pose significant concerns for apple production (Singh *et al* 2016b). The crop requires optimal climate conditions over all phenological stages from the dormancy phase (November–March) through harvest (September–October) for good yields and characteristics that impact quality and marketability such as color, size, and flavor. For instance, inadequate chilling contributes to uneven bloom, potentially causing significant fruit damage (Louw *et al* 2023). Conversely, accelerated chill accumulation can disrupt the growth cycle and advance crop growth and flowering dates (Luedeling and Brown 2011, Djaman *et al* 2021). Warming winters and springs can lead to earlier bud break and bloom, increasing bud abscission and adversely impacting fruit set and vegetative growth (Atkinson *et al* 2013). Increasing growing degree days (GDD)—a measure of heat accumulation—can influence growth rates, cause heat stress, increase irrigation requirements, and create favorable conditions for pests and diseases (Konzmann *et al* 2013, Rajagopalan *et al* 2018, Abendroth *et al* 2019). Warmer summers can also increase heat stress, delay and disrupt fruit coloration, increase the risk of sunburn, and decrease fruit size (Warrington *et al* 1999, Darbyshire *et al* 2015, Dalhaus *et al* 2020, Willsea *et al* 2023). Therefore, understanding climate risks to apple production requires examining changes in conditions across the complete phenological cycle, which could have compounding effects on the production and economic values of apples (Wolfe *et al* 2018).

In this study, we examine the spatial patterns and historical trends in six climate metrics that capture climate conditions suitable for apples at various stages from dormancy and bud-break to harvest that are relevant for assessing climate impacts on yield, quality, and marketability of apples. We have two aims: (1) characterize the climatology of the six climate metrics and quantify their historical trends over the past four decades (1979–2022) and (2) compare the trends in these metrics across the top three apple-producing counties: Yakima (Washington), Kent (Michigan), and Wayne (New York) (figure 1). Washington State accounts for more than 60% of U.S. apple production, with much of the production coming from Yakima County. Yakima is the leading apple-producing U.S. county that produces several premium apple varieties such as Cosmic Crisp, Honeycrisp, Cripps Pink, Gala, and Fuji (WSU Tree Fruit Extension).

Our study region spans the U.S as these metrics are also relevant for other perennial tree fruit and berries such as blueberries, peaches, and cherries that are grown in several states. Although the specific climate thresholds used to define these metrics will vary by crop, the general trends in these climate metrics should still be informative in assessing the impact of changing climate conditions to other tree fruit crops. Although we do not quantify impacts on yields or quality because of unavailability of suitable data, characterizing historical changes in climate metrics affecting the production of perennial tree fruit can inform subsequent research evaluating how these changes are affecting their production, for which there is currently limited literature. It is also the first step to developing reliable climate projections for such metrics to inform adaptation and management strategies among stakeholders, farmers, and the agricultural sector.

2. Materials and methods

2.1. Datasets and study region

We obtained daily maximum ($T_{\max}$) and minimum ($T_{\min}$) temperatures from the high-resolution (4 km, 1979–2022) GridMET Climatology Lab dataset (Abatzoglou 2013).

Our study assesses the spatial climatology over the current climate normal period (1991–2020) and trends over the past four decades (1979–2022) across the contiguous U.S. We use U.S National Climate Assessment regions shown in figure 1 for discussion of observed trends (USGCRP 2018). We also examine the time series of the climate metrics across the leading apple-producing counties: Yakima (Washington), Wayne (New York), and Kent (Michigan) (figure 1). Yakima county, Washington has a semi-arid climate with cold and wet winters and hot and dry summers while Kent and Wayne County have humid continental climates characterized by warm and humid summers. These counties account for 53,703 acres (13.1%), 27,761 acres (6.8%), and 14,153 acres (3.4%) of the total national acreage of 411, 262 (USDA NASS CoA 2022).

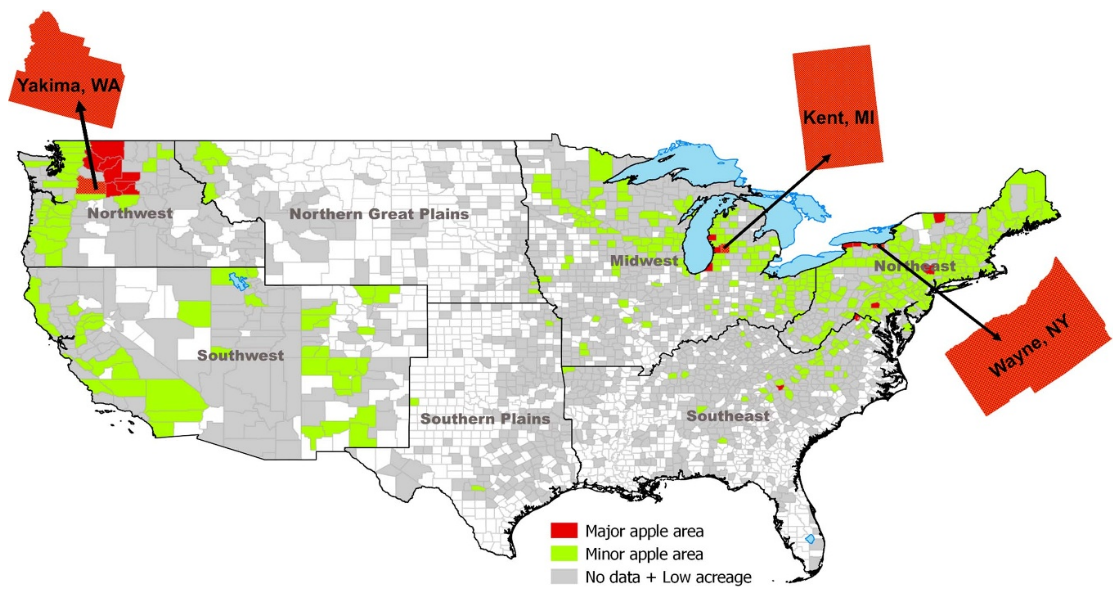

Figure 1. Map of major (red) and minor (green) apple-producing counties in the U.S. Counties whose cumulative percent acreage adds up to 75% are considered major apple-producers and the remaining counties with cumulative acreage between 75% to 99% are minor apple-producers. Gray counties have values that are either withheld or low (contributing to the remaining 1% of apple acreage). The three counties separated out are the top apple-producing counties in the U.S.—Yakima (WA), Kent (MI), and Wayne (NY). Also shown are seven US NCA regions used for reference.

2.2. Climate metrics

We examined the following six climate metrics that capture climate conditions over the apple phenological cycle and are relevant for assessing risks to growth, quality, and harvest (figure 2):

(a) **Chill portions (CPs)**: For assessing the transition between endo- and eco-dormancy, certain number of hours of chill accumulation between specific cold temperatures are vital (Bowling *et al* 2020). Insufficient chilling can lead to non-uniform bud break, increased bud abscission, and reduced flower and fruit quality (Atkinson *et al* 2013). Optimal temperatures that are beneficial for chilling are between −2 °C and 13 °C, with the most optimal temperatures occurring between 6 °C and 8 °C (Erez *et al* 1990). CPs are calculated over 1 September–31 March using the dynamic model (Erez *et al* 1990, Fishman *et al* 1987a, 1987b), which accounts for the chill 'effectiveness' of different temperatures. We analyze the CPs accumulated as of 31 March that represents the chilling accumulation from 1 September to 31 March. The chillR package (Luedeling *et al* 2023) was used to calculate CPs. CP requirements can vary between 35 and 79 CPs for different apple varieties (Darbyshire *et al* 2016, Díez-Palet *et al* 2019, Parkes *et al* 2019, Noorazar *et al* 2022).

(b) **Cold degree days**: The accumulation of cold conditions over a given period is useful for evaluating the threat of damage from extended periods of freezing temperatures (Rochette *et al* 2004). We define cold degree days as the integration of daily average temperatures below 0 °C (Bhatnagar *et al* 2018) in degree C on all days (d) between 1 November–31 March, as follows:

$$\text{Cold degree days} = \sum_{d}\left(0^{\circ}C - \frac{T_{\max}+T_{\min}}{2}\right); \quad \text{if}\,\frac{T_{\max}+T_{\min}}{2} < 0^{\circ}C\ldots \quad (1)$$

(c) **Frost risk**: Changes in the last day of frost for the season could affect the overlay between bud break timing and frost exposure and lead to loss of yields due to frost damage (Pfleiderer *et al* 2019, Park *et al* 2021). We examine changes in frost risk based on the last day of frost, defined as the last day with $T_{\min} \leqslant 0$ °C between 1 January and 31 July.

(d) **Growing Degree Days (GDD)**: Accumulation of degree days between growth-conducive temperatures is critical for flower and fruit development and growth. GDD is a measure of this accumulation between a baseline temperature and upper temperature threshold outside of which growth is minimal (Zhou and Wang 2018). We calculate GDD in degree C over January–April as relevant for bud break & flowering and January–September for the overall growth of apples (Küçükyumuk and Erdal 2012). We use 6 °C for the baseline and 28 °C for the upper threshold following the guidelines provided by the Cornell Institute for Climate Smart Solutions (2023):

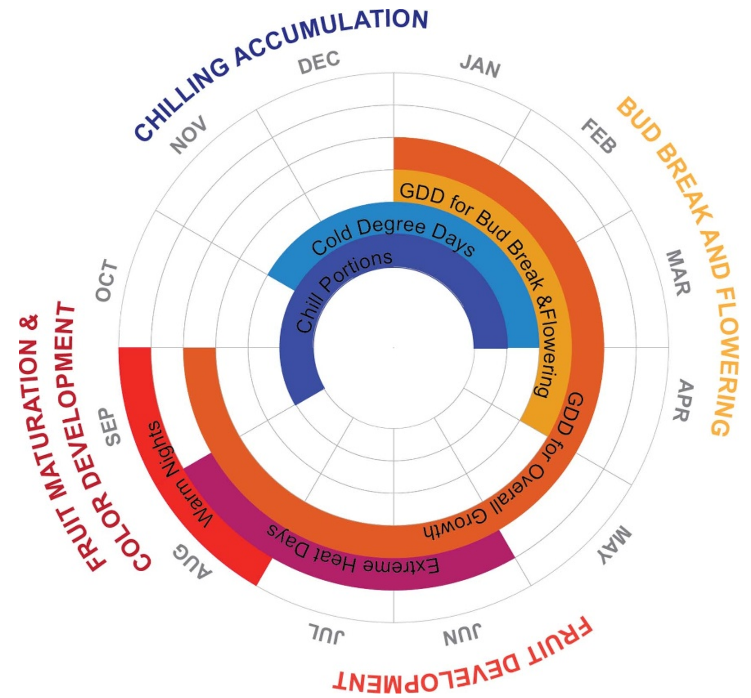

Figure 2. Months over which the six climate metrics are calculated (inner segments)—chill accumulation (September–March, dark blue), cold degree days (November–March, light blue), growing degree days for bud break and flowering period (January–April, yellow), growing degree days for overall growth (January–September, orange), extreme heat days (June–August, dark pink), and warm nights (August–September). Text on the outer edges indicates four key phenological stages.

$$\text{Growing Degree Days} = \begin{cases} \sum \frac{T_{\max}+T_{\min}}{2} - 6^{\circ}C); if T_{\min} > 6^{\circ}C and T_{\max} < 28^{\circ}C \\ \sum \frac{28C+T_{\min}}{2} - 6^{\circ}C); if T_{\min} > 6^{\circ}C and T_{\max} \geq 28^{\circ}C \quad \ldots\ldots \\ \sum \frac{T_{\max}+6^{\circ}C}{2} - 6^{\circ}C); if T_{\min} \leq 6^{\circ}C and T_{\max} < 28^{\circ}C \end{cases} \tag{2}$$

(e) **Extreme heat days:** Apples can suffer damage from sunburn when exposed to air temperatures exceeding 34 °C during the warm growing season (Darbyshire *et al* 2015). Fruit surface temperatures are greater than air temperatures (Willsea *et al* 2023) and cause sunburn browning damage when the fruit's surface temperature hits 42 °C–46 °C and necrosis when surface temperatures exceed 52 °C (Kalcsits *et al* 2017). These thresholds are variety specific and may only damage a percentage of the crop (Racsko and Schrader 2012). Given the availability of long-term air temperature data, we examine sunburn risk using daily maximum air temperatures during June–August exceeding 34 °C, during which fruit surface temperatures can likely exceed 42 °C.

(f) **Warm nights**: Optimal color development, crucial for a marketable apple, occurs when anthocyanin synthesis begins on the peel and apples start developing red and pink hues (Arakawa *et al* 1999, Willsea *et al* 2023). Harvested apples have been known to show greater red coloration with exposure to cooler nighttime temperatures during the late growing season and harvest (Fang *et al* 2019). While the temperature thresholds are still an area of active research, we use 15 °C based on personal communications from tree fruit experts and previous studies (Wang *et al* 2000) and define warm nights as days with daily minimum temperatures between August–September exceeding 15 °C.

2.3. Trend analysis

We employ simple linear regression to quantify long-term (1979–2022) trends and p-values to determine statistical significance of trends from the historical GridMET dataset. We considered trends as significant if p-values < 0.05 ($\alpha = 0.05$). This is done using the 'linregress' function from the SciPy library in Python (Virtanen et al 2020). All p-values are found in supplementary figure S1.

2.4. Potential climate damage index (PCDI)

To evaluate the overall impact of changes in multiple metrics, we define a potential climate damage index (PCDI) that synthesizes the six key climate metrics outlined in section 2.2. PCDI is the number of climate metrics that show trends in a direction that has potential to adversely impact the yield, quality aspects such as sweetness, color, cosmetic damage, storability or other characteristics that affect marketability. This index highlights regions where apple production may face increased risks due to climatic trends. Here, we assume that positive trends in cold degree days, GDD during bud-break and bloom, GDD for overall growth, extreme heat days, and warm nights, and negative trends in CPs have the potential for negative impacts. An additional assumption is that local production is adapted to local climatology. We note the caveat here that the impact of these climate trends on apple production characteristics can vary across different regions of the U.S. For instance, increased GDD might be beneficial in colder regions while detrimental in relatively warmer southern regions.

Note, we did consider using a weighted index of these metrics. However, these metrics have relevance for different aspects of apple growth and quality and there is no research to justify weights to assign to different metrics.

3. Results

3.1. Spatial patterns of climatology and trends in apple-relevant climate metrics

Figure 3 shows the spatial patterns of the climatology and decadal trends in two metrics—cold degree days that capture the risk of lethal conditions and CPs that capture chilling accumulation that is beneficial for apples. Parts of the Northern Great Plains, Midwest, and Northeast typically experienced an average of 900–1500 cold degree-days per season (figure 3(A)). Several southern states experience fewer cold degree-days (∼0–150). Cold degree-days decreased across most of the northern U.S., with the most pronounced declines of up to 70-degree-days/decade across the Rocky Mountains located in the Northern Great Plains and parts of the Southwest (figure 3(i)).

Different varieties of apples grown across the U.S. require different CPs for endo-dormancy. Average CPs on 31 March representing chilling accumulation between 1 September–31 March, were the highest for coastal areas of the Northwest (∼140 CP; figure 3(B)). Much of the Northwest, Southwest, Northern Great Plains, and Northeast have average CP of ∼84–112 while CP is lower in the Southern Plains, Southeast, and southern Southwest regions (figure 3(B)). Over the past four decades, CPs increased across the Northwest and Northern Great Plains, exceeding 5 CP/decade in some areas (figure 3(ii)). CPs also increased in the upper Midwest and Northeast by ∼1–2 CP/decade), while the southern states of the U.S. experienced little to no change of between 0–2 CP/decade (figure 3(ii)). While there was increased seasonal chill accumulation from November through March in the northern latitudes, the increase was driven primarily by the late winter season changes (February and March; figure S3).

Next, we evaluated the climatology and decadal trends in GDD for two periods—bud break and flowering (January–April) and overall growth (January–September)—that capture the accumulation of heat between certain temperatures (figure 4). GDD leading to apple bud break and flowering varied from ∼900–1500 for the Southern Plains, Southeast, and Southwest (figure 4(A)) to 0–300 degree-days in the upper Midwest, Northwest, and Northeast. Similarly, GDD for overall growth spanning January-September varied from 3600–6000 degrees-days over parts of the southern and midwestern U.S. to ∼600–2400 degree-days across the Northwest and ∼1200–2400 degree-days in the upper Midwest and Northeastern U.S. (figure 4(B)). Across several southern U.S. states, GDD over the bud break and flowering period increased by >25 degree-days/decade and experienced moderate declines of ∼0–10 degree-days/decade in the upper Midwest and Northwest (figure 4(i)). In contrast, GDD for overall growth increased across most of the US with the largest changes exceeding 70 degree-days/decade across all regions except the Northern Great Plains and parts of the Midwest (figure 4(ii)). Trends in January–September GDD are more moderate or negligible in parts of the Northern Great Plains (figure 4(ii)).

High daytime temperatures in the summer can pose sunburn risk for apples during fruit development and warm nighttime temperatures in fall can affect apple color development (figure 2). Figure 5 shows the climatology and decadal trends in two climate metrics that capture these conditions- extreme heat days representing daily maximum temperatures >34 °C during June–August and warm nights representing daily minimum temperatures >15 °C in August and September. The number of extreme heat days are typically highest in parts of the Southwest and Southern Plains that experience an average of 54–90 days per season. Although in the northern latitudes, key apple growing regions like eastern Washington (Northwest) experienced 9–27 extreme heat days (figure 5(A)) per season that pose sunburn risk to apples. The Northwest and Southwest U.S. along with the Southern Plains experienced increases in extreme heat days (1–5.5 days/decade; figure 5(i)). Conversely, parts of the Midwest, Northern Great Plains, Northeast, and Southeast experienced decreases in extreme heat days ranging from 0.5–2.5 days/decade (figure 5(i)).

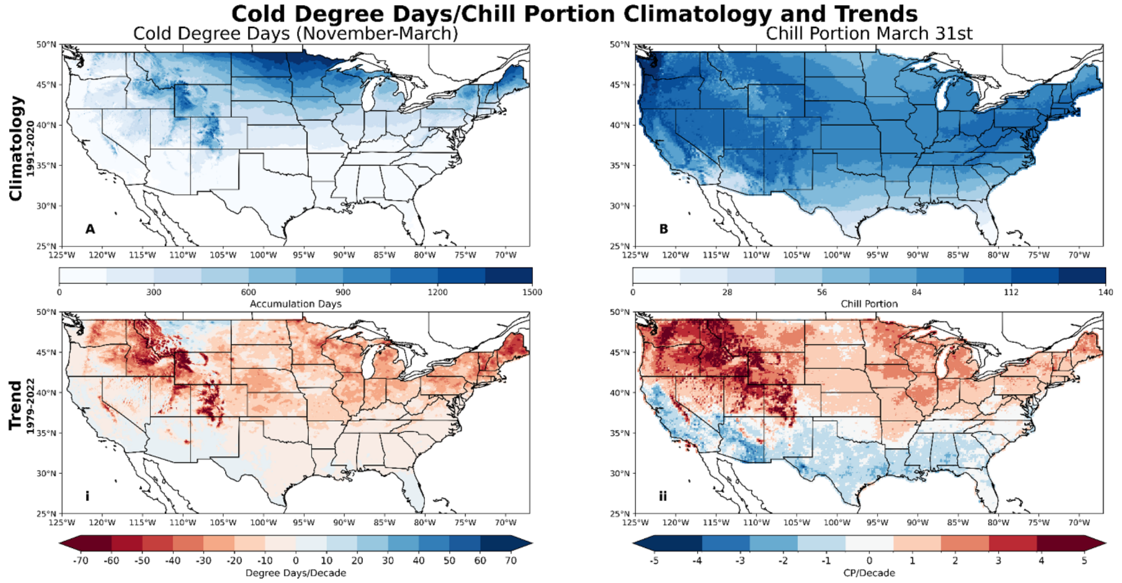

Figure 3. (A)–(B) Climatology (1991–2020) and (i–ii) decadal trends (1979–2022) for cold degree days and chill portions (CP) across the continental U.S. Significance of trends is shown in supplementary figure S2. Note red colors indicate decreasing trends for CDD but increasing trends for Chill Portions, which both point to trends consistent with warming.

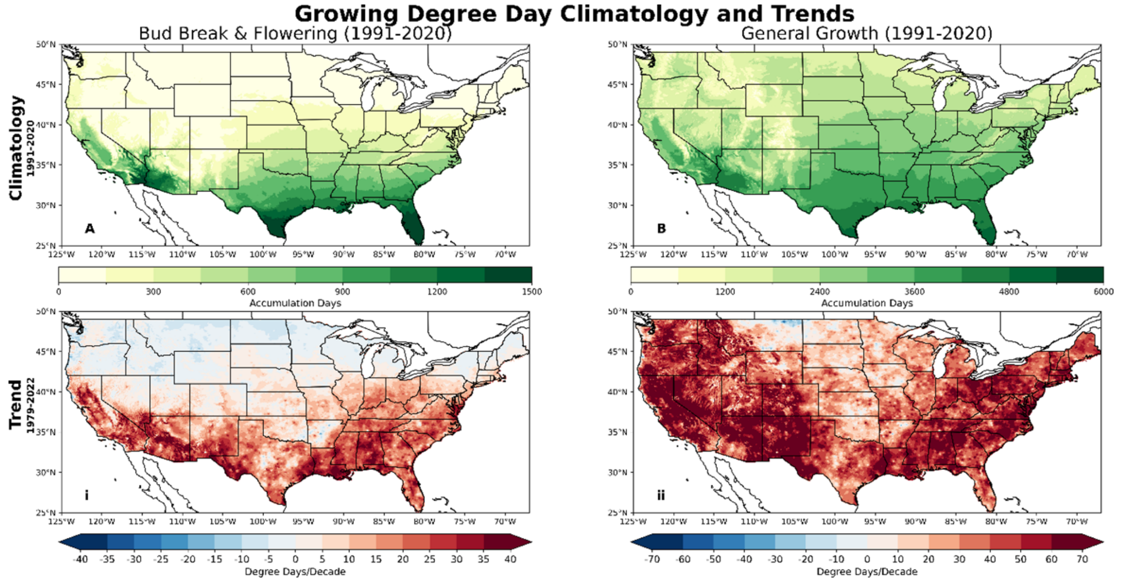

Figure 4. (A)–(B) Climatology (1991–2020) and (i–ii) trends (1979–2022) for growing degree days calculated over January–April and January–September across the continental U.S.

Despite relatively low likelihood of summer daytime heat, the likelihood of warm nights during the early fruit maturity and coloration period (August–September; figure 2) was substantially higher across the Southeast region of the U.S. (figure 5(B)). Much of the Southern Plains, Southwest, and Southeast experienced on average 48–60 warm nights. The number of warm nights is considerably lower (<24) across much of the Northwest, upper Midwest, Northern Great Plains, and Northeast. Nighttime temperatures are increasing across most of the U.S with the largest changes across the Southwest and Northeast regions, which have the potential to adversely impact apple sweetness and color development (figure 5(ii)).

Changes in these six-climate metrics collectively illustrate the potentially compounding negative effects of climate change on the yields and quality of apple production across the U.S. The spatial variations in these metrics across the U.S. are broadly driven by the spatial patterns of trends in maximum and minimum temperatures (figures S3 and S4). For instance, the greater increases in CPs across the northern half of the U.S. (figure 1) are consistent with the higher rate of warming in the higher latitudes, particularly in January. The more moderate changes in cold

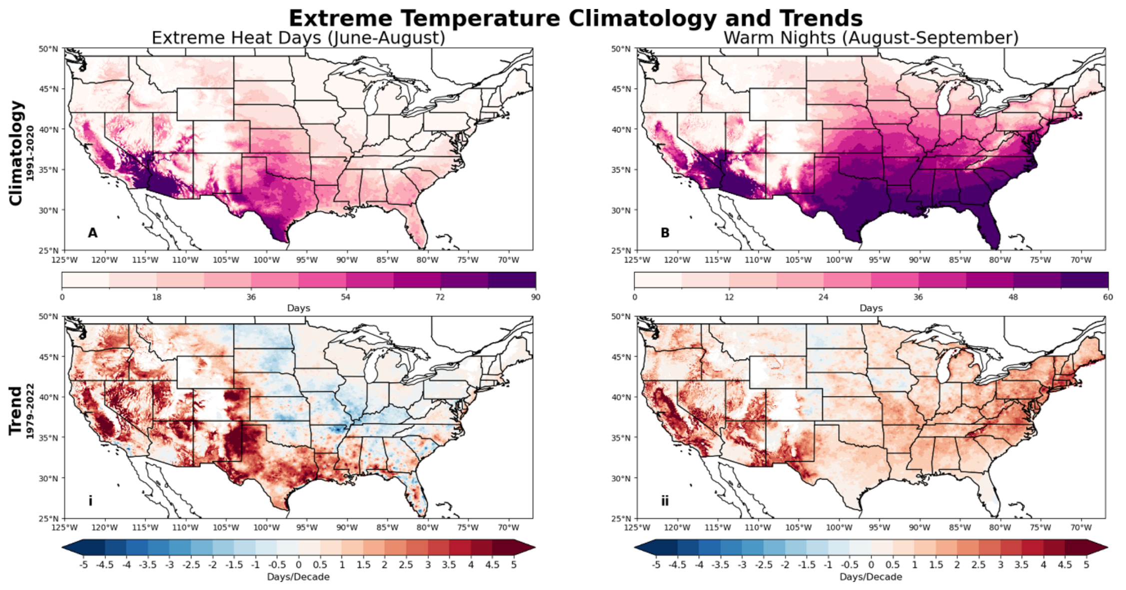

Figure 5. (A)–(B) Climatology (1991–2020) and (i–ii) trends (1979–2022) for extreme heat days ($T_{max} > 34$ °C) during June–August and warm nights ($T_{min} > 15$ °C) during August–September across the continental U.S.

degree days, CPs, and bud-break and flowering GDD across the Great Plains and parts of the northern U.S. are likely driven by the regional cooling trend in February (figures S3 and S4). Further, the relatively more widespread increases in January–September GDD and summer heat extremes across the western U.S. are associated with the relatively higher rate of warming across the region compared to the eastern U.S. in several months of the year. These regional differences are particularly amplified in the summer (figures S3 and S4).

Currently, most major and minor apple growing counties are located in the Northwest, Midwest, and Northeast and some minor apple growing counties are in the Southwest and parts of the Southeast (figure 1). States in the Northwest that contribute the highest to national apple production have experienced significant and large changes in several metrics including decreases in cold degree days and increases in CPs, GDD for overall growth, extreme heat days, and warm nights (figures 3–5(i–ii)). The Midwest and Northeast have also experienced similar but more moderate changes in chilling accumulation metrics, increases of similar magnitude in GDD for overall growth, and more widespread increases in GDD for bud-break and flowering and warm nights. These trends have the potential to reduce apple yields by disturbing the phenological cycle, accelerating growth into periods that would result in higher exposure to harmful temperatures, and to reduce apple quality via sunburn and lack of color development.

3.2. Trends in top apple-producing U.S. counties

To assess changing risks in the highest apple-producing counties, we quantify the characteristics (supplementary table 1) and 43-year trends (figure 6) in the six-climate metrics across the leading apple-producing counties—Yakima County, WA (Black), Kent County, MI (Blue), Wayne County, NY (figure 1). Among these three counties, Kent County has the highest interannual variability (standard deviation) in most metrics. All three counties have experienced changes in climate conditions during multiple phenological stages of apples. However, trends across these counties vary substantially due to their geographical locations, which influence their climatology, exposure to climate trends, and consequently, their vulnerability to changing climate conditions. Yakima County, the highest producer of apples in the U.S., experienced the most significant (at the 5% level) and largest changes amongst these three counties in five of the six metrics.

Cold degree days significantly decreased by 2.5-degree days/year or 107.5-degree days from 1979 to 2022 (figure 6(A)) and last day of frost significantly advanced by ~28 days since 1979 (0.65 days/year; figure 6(B)) for Yakima County. Kent and Wayne counties also had fewer cold degree days, but those changes are not significant despite the magnitude of the trend in Kent County being larger than in Yakima, due to high interannual variability. Despite these trends towards fewer cold degree days, 2013–2014 and 2014–15 recorded the highest cold degree days in these counties. These were associated with an amplification of the North American Winter Temperature Dipole (Wolter et al 2015, Singh 2016). These counties also did not experience significant changes in the last day of frost. It is noteworthy that Wayne County experienced little interannual

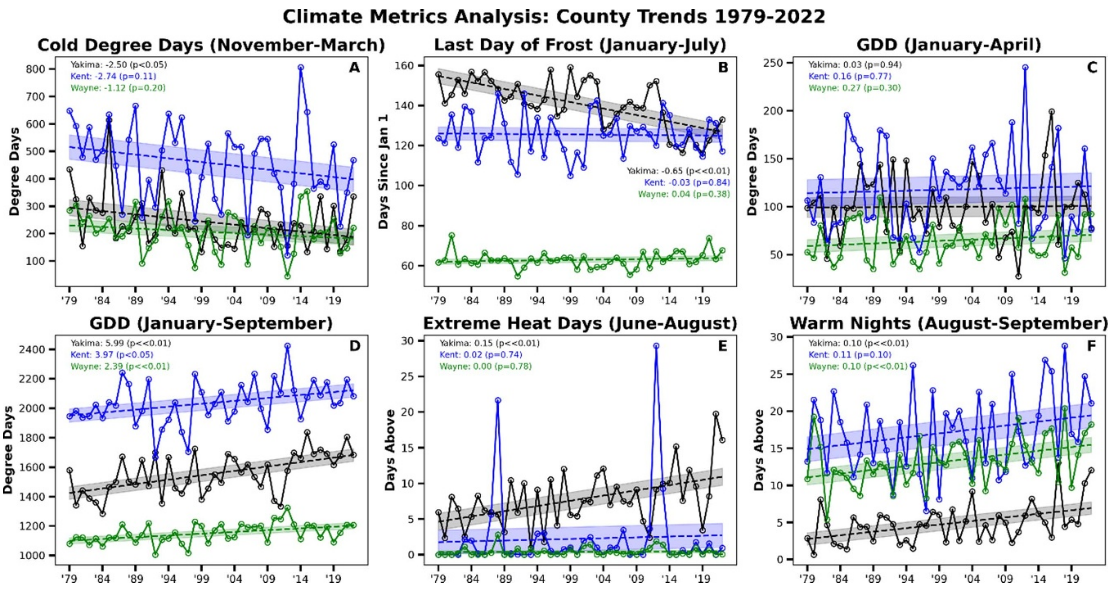

Figure 6. (A)–(F) Trends (1979–2022) for cold degree days (A), last day of frost (B), GDD calculated during bud break and flowering (C), GDD during general growth (D), extreme heat days (E), and warm nights (F) for Yakima County, WA (Black), Kent County, MI (Blue), Wayne County, NY (Green) shown in the map above. Shading represents 95% CI. See figure 1 for locations of these counties.

variation for the last spring frost day in Wayne County, so relatively small deviations had notable effects. For instance, the late frost in April 1981 substantially impacted apples and other tree fruits with fruit growers in the county losing an estimated \$28 million due to frost damage (figure 6(B), green line) (Faber and Times 1981).

Early season GDD leading into bud break and flowering showed no significant change amongst all the counties (figure 6(C)). However, all three counties experienced significantly higher GDD over January-September, with Yakima (∼6 degree-days/year), Kent (∼4 degree-days/year), and Wayne (∼2.4 degree-days/year) over 1979–2022 (figure 6(D)). In addition to experiencing the largest increase in January-September GDD, Yakima was the only county that experienced significant increases in the number of extreme heat days, averaging about ∼0.15 days/year or 6.45 days between 1979–2022. Notably, Yakima County experienced 20 days with temperatures >34 °C in 2021, the highest on record, followed closely by 16 days in 2022. While Kent and Wayne County typically experienced fewer extreme heat days with no significant increases during the study period, Kent County had two notable summers – 1988 and 2012 – with 21 and 29 extreme heat days respectively, which were substantially higher than the average (figure 6(E)) (Holmstrom and Ellefson 1990, Whetstone 2014, Lupher *et al* n.d.). All three counties have experienced significant increases in fall warm nights exceeding 0.10 days per year or ∼4.3 days over our entire analysis (figure 6(F)). Yakima also had the third highest number of warm nights in 2021, which also contributed to the impacts on WA apple producers in 2021.

3.3. Potential climate damage index

The maps in figure 7 illustrate the spatial distribution of the PCDI across the U.S. These maps highlight regions subject to multiple climate trends that are potentially harmful to healthy apple growth, quality, and production. The left panel shows that the Northwest, particularly Yakima County—the largest apple-producing county in the U.S.—exhibits up to five detrimental trends, while other areas, such as the Northern Great Plains, show two to three detrimental trends. In contrast, the right panel, which applies a stricter >10% change per decade threshold, reveals that only the Northwest, Southwest, and Northeast exhibit more than two large detrimental trends. This suggests that while multiple regions are experiencing adverse climate impacts, the severity and extent of these trends are more concentrated when using the stricter threshold. These areas with large potentially detrimental trends across multiple metrics overlap with the top apple production regions of the US (figure 1).

4. Summary and discussion

This study provides the first comprehensive assessment of the long-term trends in multiple climate metrics relevant to the cultivation of apples in the U.S. Previous studies have examined individual metrics during parts of the phenological cycle but analysis of multiple metrics across different phenological stages has not yet been conducted. Our findings suggest that Northwest, Midwest, and Northeast have experienced substantial changes in at least three of the six climate metric that have the potential for negative impacts including more GDDs in the early season leading into

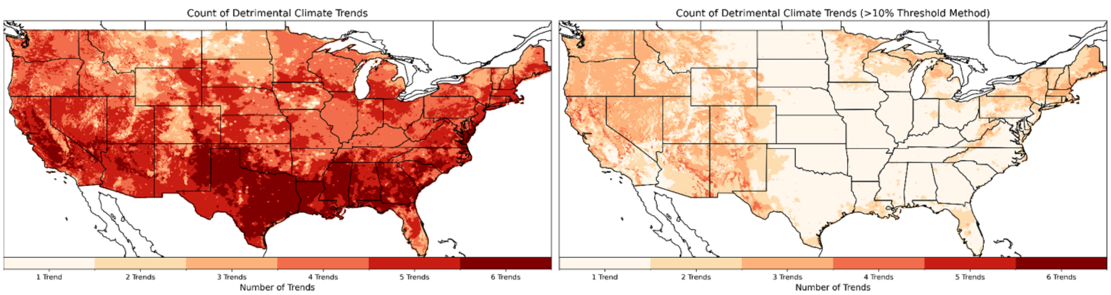

Figure 7. Potential climate damage index across the contiguous United States. The left panel illustrates the spatial distribution of the number of detrimental trends (including non-significant trends) across all six metrics discussed in section 2.2. Lighter red colors highlight fewer number of trends and darker red highlight a greater number of trends that are potentially detrimental. The right panel exhibits the number of detrimental trends with a change greater than 10% per decade following the same color scheme.

early bud-break and flowering, more GDDs over the entire growing season, and more extreme heat days (figures 3–5). These are regions where the highest apple growing areas are located. We introduce a new potential climate damage index to represent the consistency in the directionality of trends in the six metrics towards negative impacts for apples. In particular, Yakima County, the highest apple-producing county has experienced significant changes in five of the six metrics analyzed.

We note that there is substantial spatial variability in these metrics across the U.S. Parts of the Northern Great Plains and upper Midwest have experienced opposite or negligible trends in some metrics associated with contrasting trends in monthly temperatures (figures S3 and S4). These regional and seasonal differences are driven by differential rates of warming across the U.S.—higher rates of warming at the higher latitudes in winter, greater warming over the western U.S., and cooling over parts of the central and southern U.S. The warming pattern has been attributed to anthropogenic warming, while the cooling pattern in central and southern U.S. is driven by a combination of anthropogenic aerosol pollution, agricultural intensification including irrigation, and natural climate variability (Marvel *et al* 2023).

Overall, the observed climatic changes can have both beneficial and adverse effects for apple cultivation depending on the region. Fewer cold degree days and earlier last day of frost could be beneficial by reducing exposure of apples to freezing temperatures allowing the use of less cold hardy crop varieties. Yet, it could also diminish plant cold hardiness, increasing vulnerability to extreme cold events (Wisniewski *et al* 2018). Key apple production regions are concentrated in the northern U.S. Given that these regions see increases in chill accumulation, the risk of insufficient chill accumulation is likely low, but an increased rate of chill accumulation can impact the heat requirements for bloom (Noorazar *et al* 2022) and indirectly impact the timing of bloom and related risk of frost damage. Additionally, accelerated early season GDD accumulation will accelerate the bloom time (Noorazar *et al* 2022) and can lead to increased frost risk during late spring freezes. Accelerated GDD accumulation may advance all subsequent phenological stages as well. Accelerated GDD accumulation and resulting shorter time to maturity are often associated with decreases in yields (Rajagopalan *et al* 2018). Early maturing could increase risk of exposure to damaging heat, if this happens during the hotter summer months. Moreover, accelerated maturity can hinder post-maturity red color development, an important quality impacting the price of apples, which requires exposure to cooler nighttime temperatures (Willsea *et al* 2023). This issue is further compounded given a general warming of fall nighttime temperatures in addition to advancement of maturity to warmer times of year. In addition, GDD increases along with other climate changes might also herald stressors, such as water scarcity (Rosenzweig and Hillel 2000, Meza *et al* 2023). Furthermore, increasing hot extremes increase sunburn risk, which, alongside earlier maturity periods, compounds the challenges faced by growers and highlights the need for risk management (Aćimović and Jentsch 2020).

We note a few caveats in our study. *First*, our analysis focuses primarily on analyzing temperature-based climate metrics that have the potential to affect apple production without directly analyzing apple production and quality data. Data on apple yields are limited at the county resolution in the USDA NASS census and surveys. Higher spatiotemporal resolution data on apples and other tree fruit are necessary for analyzing the magnitude of climate impacts. On the quality side, while tree fruit physiologists have a general sense of how different factors affect marketability, national efforts to compile data scattered across research groups into a central repository and develop models are just commencing. *Second*, we also do not analyze precipitation metrics since most major apple producing regions are irrigated in the major apple growing areas. Changes in precipitation could indirectly affect crops via affecting irrigation water availability. *Third*, changing climate conditions could indirectly affect yields and quality via other stressors including changes in the growth, distribution, and dynamics of pests, diseases, pathogens, and pollinators such as Woolly Apple Aphids, Codling Moth, and fire blight that already damage apples in many regions (Walker *et al* 1988, Asante *et al* 1991, Coakley *et al* 1999, Beers *et al* 2010, Duffy 2012, Rajagopalan *et al* 2024). Assessing other relevant climate variables and climate-driven changes in pests and disease are important for gaining a more comprehensive understanding of how climate change is affecting the production of perennial tree fruit such as apples.

The identified climate changes are broadly relevant to other tree fruit with similar phenology. While the specific thresholds for computing metrics in our study can vary from fruit to fruit (or even by cultivar), the general direction of trends provide a broader context of change for tree fruits. Collectively, our findings imply that changing climate conditions could provide some benefits but also have the potential to negatively impact high-quality apple and perennial tree fruit production in many regions of the U.S. Tree fruit hold substantial economic value, contributing billions of dollars to the economy, and offering important nutritional benefits as a staple fruit for balanced diets. Our analysis of the climatology and historical trends of these metrics can inform future work on how such climatic changes are collectively affecting the different characteristics of apple and other tree fruit. Changes in multiple climate metrics during different phenological stages could have compounding negative impacts on the yield, quality, and characteristics such as color development, cosmetic damage due to sunburn, and sweetness of fruits, which could further be amplified by water scarcity or increases in pests and diseases. Some of these negative impacts could be minimized via adaptation strategies such as protective netting, evaporative cooling, chemical management to delay or advance growth, and changing varieties. However, the scale of impacts during recent extreme hot summer seasons and extreme cold winter seasons across parts of the U.S. have highlighted the existing vulnerability of our production systems due to the damage they caused to a variety of crops. The changes we have identified in our study underscore the urgent need for increasing investments in innovative adaptation strategies to ensure the sustainability, resilience, and economic viability of the tree fruit industry to multiple climate stressors.

Data availability statement

All computations were performed on WSU's Kamiak High-Performance Cluster. We acknowledge and thank several organizations for making their data publicly available. All meteorological data were originally downloaded at the daily resolution from the UC Merced Climatology Lab available at www.climatologylab.org/gridmet.html. Shapefiles used for this study were found at the U.S. Census Bureau, Department of Commerce, available at https://catalog.data.gov/dataset/tiger-line-shapefile-2019-nation-u-s-current-county-and-equivalent-national-shapefile and for NCA5 shapefiles available at https://atlas.globalchange.gov/datasets/nationalclimate::nca-regions/about.

Code to replicate and create figures can be found in the following GitHub Repositories: (GridMET): https://github.com/shawnatwsu/Changing-Climate-Risks-for-High-Value-Tree-Fruit-Production-across-the-United-States.

The meterological input data that support the findings of this study are openly available at the following URL/DOI: www.northwestknowledge.net/metdata/data/.

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