Received: 15 February 2023 | Accepted: 6 September 2023

DOI: 10.1002/csc2.21101

Crop Science

SPECIAL ISSUE: CLIMATE CHANGE VIRTUAL ISSUE

Corn response to long-term seasonal weather stressors: A review

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Assigned to Associate Editor Maria Otegui.

Abstract

Long-term weather patterns (environmental conditions or stresses exceeding 10 days in length) have the potential to influence corn (*Zea mays* L.) growth, development, and yield. This review summarizes the current knowledge (with emphasis placed on the Midwestern U.S. production environment) on how long-term weather conditions affect corn growth and yield, including (i) drought and heat stress, (ii) solar radiation, and (iii) distribution of heat unit accumulation during the season. Each section contains summaries of how these environmental factors influence corn growth and yield and provides context into past events experienced. The focus of the review is on dent corn grown for grain production, though relevant issues related to other types (i.e., silage corn) are included. This review also discusses agronomic recommendations or considerations to help alleviate the negative effects of stress conditions and identify areas where future research would be beneficial to continue improving the resiliency of corn cropping systems. Periods of high heat and water deficit as well as limited light availability challenge the ability to maximize yield production in corn. Temperature affects crop growth and development through the season, and accurately describing phenological progression using heat unit accumulation is a challenge. Advances in corn breeding and genetics, hybrid selection, and agronomic management practices will be key to ensuring long-range productivity and fully leveraging possible benefits from the shifts in long-range weather patterns.

1 | INTRODUCTION

Corn is a major crop grown in the United States, with most of its production centered in the Midwestern United States (Figure 1a,b). Factors affecting crop production include genetics, environment, and management practices (Messina, Ciampitti, et al., 2022; Messina, Rotundo, et al., 2022; O. Ortez, Lindsey, et al., 2022; Rizzo et al., 2022). Environmental conditions across this region vary on spatial and temporal scales, including soils, weather, and accumulation of heat units growing degree days (Anandhi, 2016; Angel et al., 2017;

Abbreviations: CRM, comparative relative maturity; GDU, growing degree unit; PAR, photosynthetically active radiation; PPFD, photosynthetic photon flux density; PTQ, photothermal quotient; RUBISCO, ribulose-1,5-bisphosphate carboxylase/oxygenase.

Crookston et al., 2021). As climatic conditions continue to shift throughout the country, the likelihood of dust storms or haze from wildfires may increase (Orner, 2021). While different regions experience different local conditions during the season, variations from the average weather conditions at different growth stages can affect productivity.

In a recent report based on crop modeling, Rizzo et al. (2022) reported that climate and agronomic improvements played significant roles in corn yield gains in favorable environments in the Western United States (Nebraska) from 2005 to 2018 under irrigated conditions. Other studies have reported that genetic contributions to grain yield improvement are still major contributors (Messina, Ciampitti, et al., 2022; Messina, Rotundo, et al., 2022), especially under rainfed conditions. Solar brightening has also been identified as contributing 27% toward yield gains in the U.S. Midwest from 1984 to 2013 (Tollenaar et al., 2017). These studies highlight that improvements in crop agronomics and plant breeding hold significant roles in maximizing crop productivity and profitability when favorable environments exist. The genetic × environment × management interaction effect is evident in the crop season. It is important to assess how longer term weather patterns (>7–10 days) and environmental conditions affect corn growth and yield. Conditions such as heat and drought (often linked during the corn production season in the Midwestern United States), solar radiation, and distribution of heat unit accumulation over the season can affect crop growth and yield. The objectives of this review are to summarize the effects of these long-term weather patterns on corn production and identify management considerations to mitigate potential losses and propose areas where future research should be conducted to improve yield when experiencing these weather conditions.

Core Ideas

- Most current management strategies for addressing long-term weather stress are employed preemptively.
- There is a continued need to improve upon current crop phenology models to accurately forecast crop development.
- Continued research on genetic × management interactions with the environment is essential to assess crop tolerance.
- Crop advances (e.g., breeding, hybrid selection, and agronomics) are key to ensure long-range productivity from shift.

Lobell and Field (2007) indicated that non-complex information such as seasonal air temperatures and precipitation can explain about 30% or more of the year-to-year variability on global crop yields in the world's six largest crops, including corn. In their report, corn, wheat (*Triticum aestivum* L.), and barley (*Hordeum vulgare* L.) showed a clear negative yield response to higher air temperatures. Based on this, they estimated that with warmer weather between 1981 and 2002, annual combined losses of these three crops were about 40 Mt, equivalent to about 5 billion USD per year. It was acknowledged, though, that these losses have been largely offset by introducing new genetic and agronomic strategies and technologies; weather stress conditions cannot be prevented, but negative plant responses may be able to be mitigated.

2 | DROUGHT AND HEAT STRESS

An increased frequency of drought events has been associated with climate change, and it has been predicted that these conditions will be more severe and have a broader spread in the future (Dai, 2013). Lobell et al. (2008) predicted that rainfall would become more erratic in the future as temperatures continue to increase. The second half of the 21st century is expected to be drier than any other period in the U.S. Central Plains and Southwest records (Cook et al., 2015). Cereal yields are adversely affected by drought, and among cereals, corn is one of the most sensitive crops (Daryanto et al., 2016). Bevacqua et al. (2022) mentioned future droughts in simulations using 2˚C higher global temperatures are predicted to coincide with moderately hot extremes. Weather extremes, particularly drought and heat, pose significant challenges not only to farmers and growers around the world but also to corn prices and crop security, especially in regions of the developing world (Chung et al., 2014).

2.1 | Events reported in the United States and yield implications

Corn yield losses can be affected by many factors, including extreme weather (Lobell & Field, 2007; O. A. Ortez, McMechan, et al., 2022) such as drought and heat. The occurrence and intensity of drought can vary annually and geographically (Figure 2). Yield losses due to drought, which are often associated with heat (Barnabás et al., 2008), have a significant detrimental effect on corn-producing regions (Ao, Russelle, Varga, et al., 2020; Campos et al., 2006; Chung et al., 2014; Lobell & Field, 2007).

For example, the widespread drought in 2012 (Figure 2b) contributed to production losses (Figure 3) of 23% in the United States compared to U.S. yield trends (USDA-NASS, 2013). Drought and heat are not only detrimental to corn during grain-filling stages; prolonged periods of heat coupled with the absence of water early in the season compromise crop establishment, early growth, pollination, and water use,

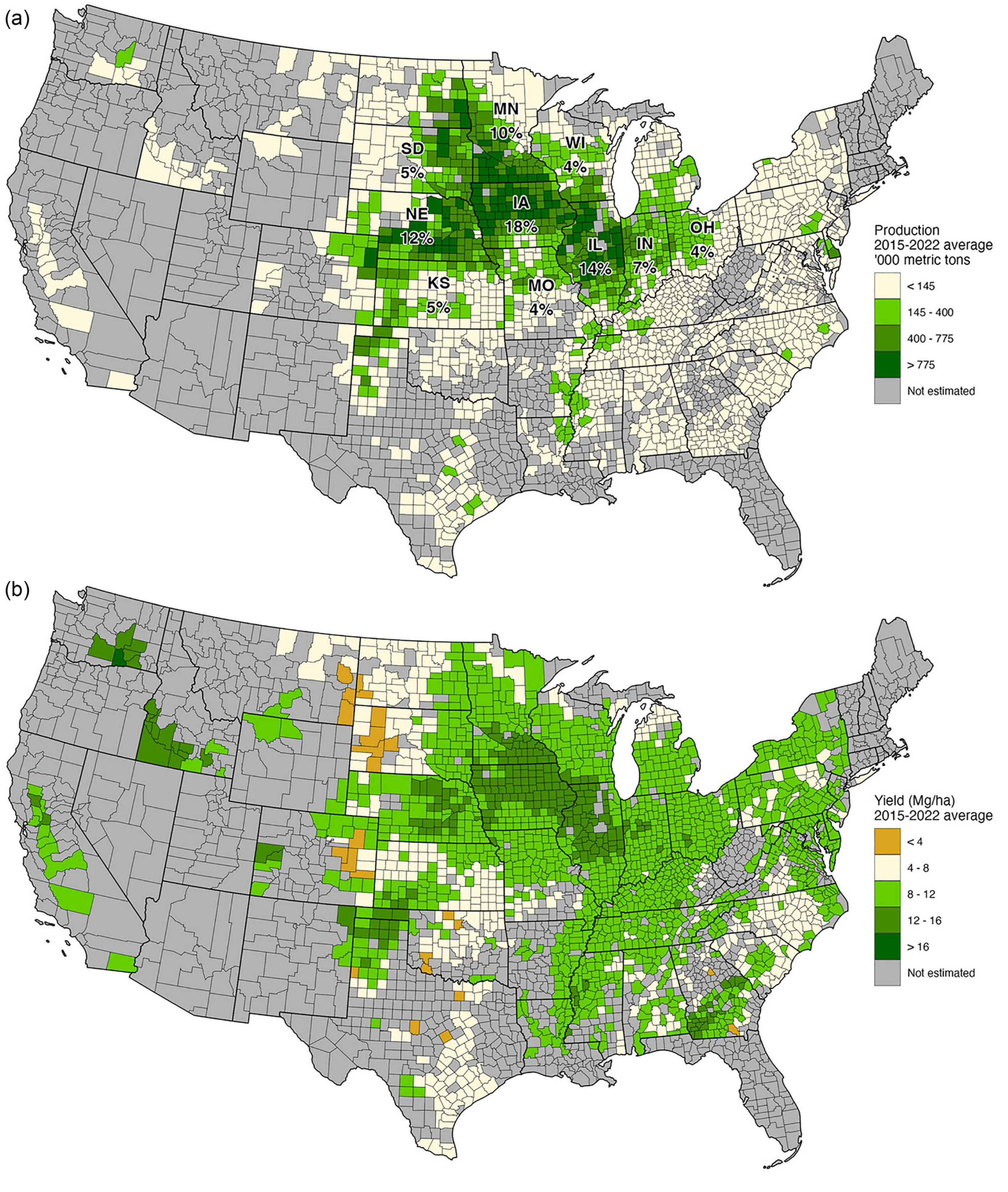

FIGURE 1 (a) Map depicting U.S. production of corn from 2015 to 2022. Percentage (%) values indicate the percent of national production. (b) Map depicting U.S. yield (Mg ha^{-1}) for county-level averaged from 2015 to 2022. *Source*: USDA-NASS. Maps: Leonardo Bastos.

which are all critical to achieving high yields (O. A. Ortez, McMechan, et al., 2022).

In the Central and Eastern U.S. Midwest, corn is grown primarily under rainfed conditions. On the other hand, corn in the Western Midwest is produced under irrigated (3.2 million ha) and rainfed (4.1 million ha) conditions (Grassini et al., 2009). Between 2000 and 2019, corn production was impacted by drought during reproductive stages (grain filling) in the U.S. Midwest in nine years out of the 20-year period (Ao, Russelle, Varga, et al., 2020; National Drought Mitigation Center, 2022) and was widespread in 2012 throughout the entire U.S. Midwest (Figure 2b). Particularly in Kansas and Nebraska, yields

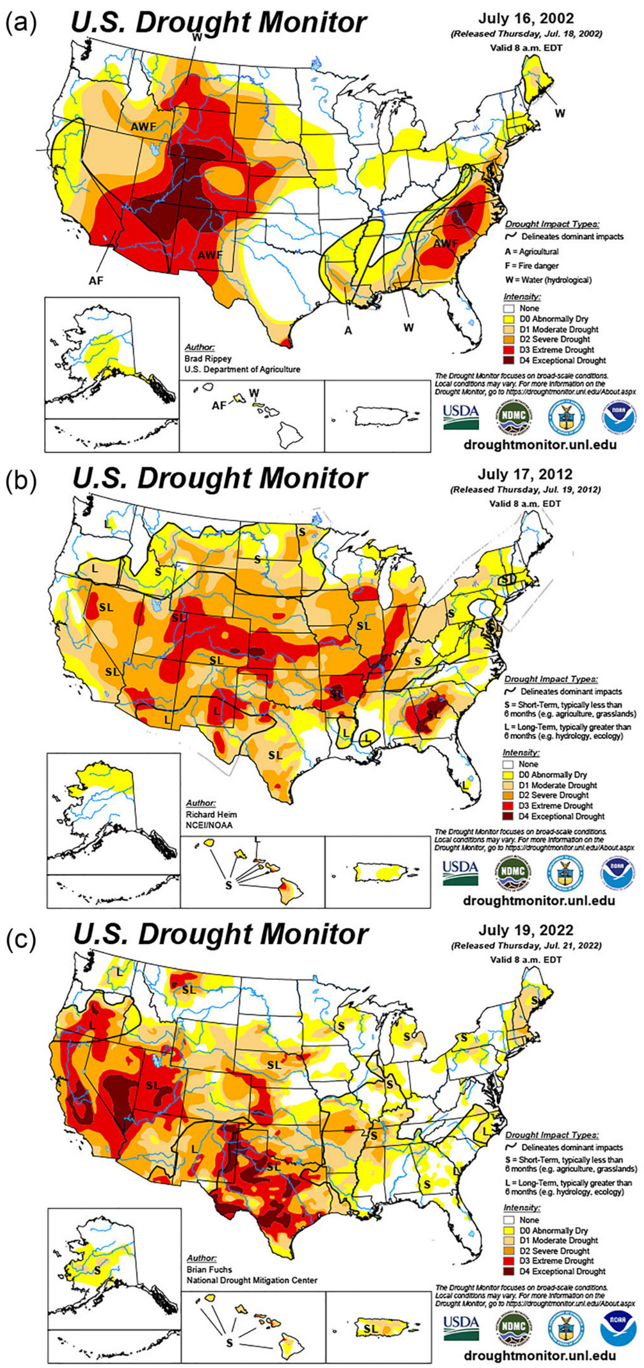

FIGURE 2 U.S. drought monitor maps for mid-July in 2002 (a), 2012 (b), and 2022 (c). The U.S. Drought Monitor is jointly produced by the National Drought Mitigation Center (NDMC) at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Maps courtesy of NDMC (2022).

under rainfed conditions were drastically reduced in 2012. In Kansas, statewide rainfed yields in 2012 were 3.1 Mg ha^{-1}, while irrigated yields were 10.8 Mg ha^{-1} (Kansas Department of Agriculture, 2013). In Nebraska, rainfed corn yields in 2012 were 2.9 Mg ha^{-1}, while irrigated yields were 11.7 Mg ha^{-1} (Y. Li et al., 2020). The effects of Drought events affect the growing season in which they occur and also have a negative effect on the subsequent crop season. Chung et al. (2014) indicated that limited rainfall in a given season coupled with reduced snowfall or precipitation during the months after harvest can result in drier soils for the following crop. The risk of production losses extends into the season following the drought year, especially in areas where precipitation is lower similar to the rainfed Western U.S. Midwest.

Research on drought stress in the absence of high temperatures in the U.S. Midwest indicated that higher yields of drought-tolerant hybrids relative to lower yields of standard hybrids were dependent on the timing that stress was initiated, which was simulated through the addition or absence of irrigation (Ao, Russelle, Varga, et al., 2020). Ao, Russelle, Varga, et al. (2020) reported that the drought-tolerant hybrid showed a yield advantage only when sustained moderate drought stress occurred during silking and pollination and lasted until physiological maturity. Higher yields of the drought-tolerant hybrid (9.2 Mg ha^{-1}) under drought stress were associated with greater kernel number and higher aboveground nitrogen (N) uptake relative to the standard hybrid (8.4 Mg ha^{-1}).

2.2 | Corn breeding response to environmental conditions

For corn breeding programs, one of the main targets has historically been higher yields, with a change in yield from about 1 Mg ha^{-1} in the 1930s to about 7 Mg ha^{-1} in the 1990s in the United States (Tollenaar & Lee, 2002), and a similar overall trend that has remained through the 2020s (Rizzo et al., 2022). Most of this change has been attributed to genetic and agronomic improvements or their interactions. However, weather is the other critical piece that can affect (positively or negatively) yield trends (Rizzo et al., 2022). The development of drought-tolerant hybrids highlights the importance of weather in the advancement of new corn genetics for better crop yields (Lopes et al., 2011).

Response to climate variability and water scarcity have been strong incentives for developing drought-tolerant hybrids (Cooper et al., 2014). Drought tolerance can be defined as the ability of a hybrid to navigate stress (drought) periods by having low internal water content or by the ability of a hybrid to minimize its yield reduction associated with water stress relative to non-stress conditions (Clarke et al., 1992; Levitt, 1972; A. J. Lindsey & Thomison, 2016). Reduced lateral root branching was observed in drought-tolerant corn lines (Zhan et al., 2015). However, Messina et al. (2021) suggested that root architecture changes over time in corn have not been an overarching driver of yield gains as water extraction has been relatively unchanged. Selection for

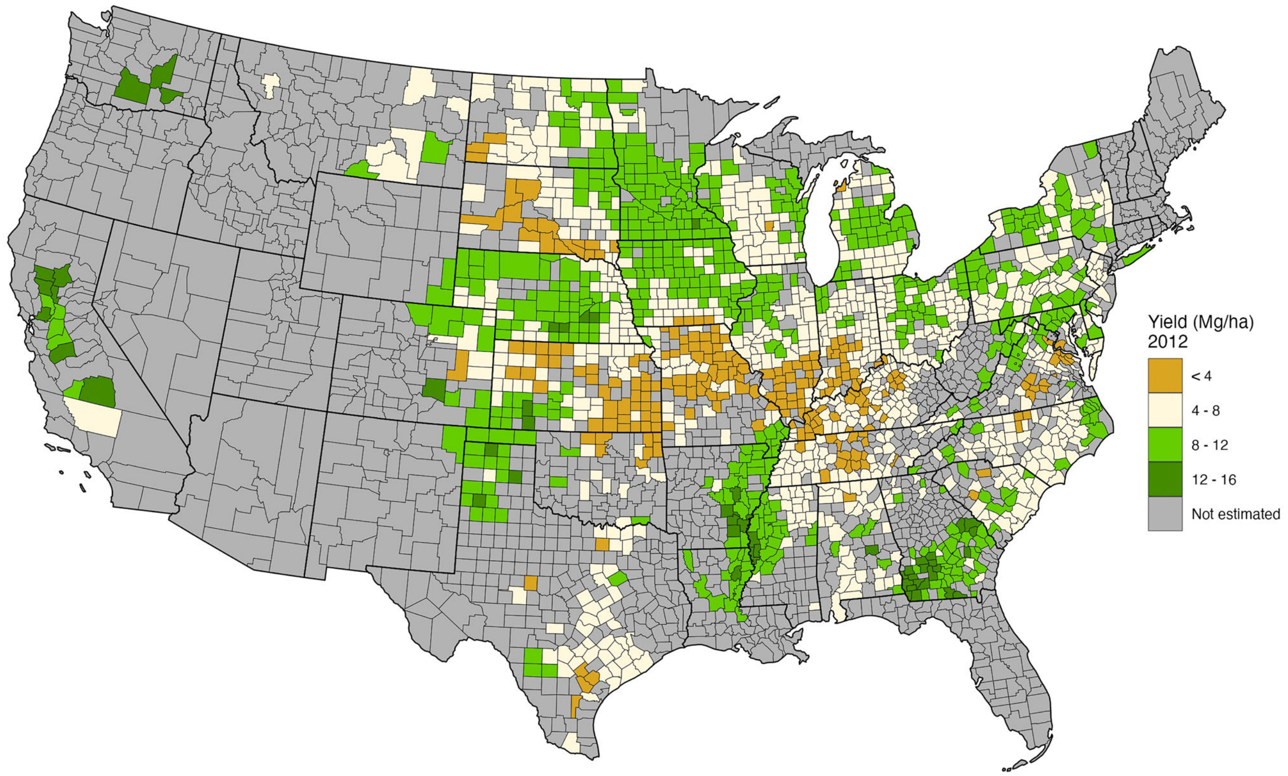

FIGURE 3 United States county-level yield map (Mg ha^{-1}) for 2012, year of widespread drought during critical timing of crop season (mid-July) across the Corn Belt. *Source*: USDA-NASS. Map: Leonardo Bastos.

drought tolerance (or "for higher yields under dry conditions") has resulted in shorter anthesis-silking intervals (Messina et al., 2021), improved efficiencies for water use (Reyes et al., 2015), lower stomatal conductance (A. J. Lindsey et al., 2018), and delayed senescence of leaves in the canopy (Ao, Russelle, Varga, et al., 2020; Finlay & Wilkinson, 1963).

As a result of breeding improvements, research reports on high ratings of drought-tolerant hybrids have shown less yield losses relative to hybrids with lower ratings if drought stress occurs (Bänziger et al., 2006). In recent years, breeding programs for drought-tolerant hybrids have released commercial products such as "Artesian" (Syngenta) or "AQUAmax" (Corteva). Transgenic approaches to improving drought tolerance have also been explored ("DroughtGard," Monsanto/Bayer). AQUAmax product development has focused on improving drought tolerance for hybrids grown in the western U.S. Midwest (Cooper et al., 2014). Cooper et al. (2014) demonstrated that an AQUAmax hybrid produced a 1.0 to 3.0 Mg ha^{-1} yield increase relative to a drought-sensitive (standard) hybrid if drought conditions were present, but the AQUAmax hybrid had 0.3–1.0 Mg ha^{-1} lower yield relative to the standard hybrid when both hybrids were grown under well-watered conditions. In another study, Messina, Ciampitti, et al. (2022) reported that AQUAmax hybrids yielded more than non-AQUAmax hybrids if water was in deficit, and the differences in this response were driven by plant density.

Adee et al. (2016) documented greater yield of drought-tolerant hybrids compared to hybrids of similar maturity without drought-tolerant designation (both AQUAmax and DroughtGard types evaluated) in four Kansas environments exhibiting high or medium seasonal evapotranspiration (>430 mm), but no advantage or penalty was documented in environments with low evapotranspiration (less than 430 mm per season). Nemali et al. (2015) reported 6% yield increases in MON 87460 (biotechnology-derived event expressing bacterial cold shock protein B, CspB) relative to a conventional hybrid control in a 3-year study (2009–2011) in fields with water-limited conditions during mid-vegetative to mid-reproductive stages. Authors associated the yield increase of MON 87460 relative to the control to better acclimatation through decreased leaf growth, which decreased water use and consequently the degree of stress in the limiting scenario. These effects also translated into more ear growth during silking that increased kernel number, harvest index, and ultimately greater grain yield. However, higher yields for drought-tolerant hybrids have not been consistent in other studies (A. J. Lindsey et al., 2015; Roth et al., 2013). That inconsistency has been in part attributed to different yield levels (Ciampitti et al., 2015; A. J. Lindsey & Thomison, 2016); below 10.7 or 12.2 Mg ha^{-1}, drought-tolerant hybrids exhibited a yield advantage over conventional hybrids in Kansas and Ohio, respectively. Yields were comparable for hybrid types above 10.7 Mg ha^{-1} yield levels in Kansas, though yields of conventional hybrids were greater than drought-tolerant hybrids in Ohio environments yielding above 12.2 Mg ha^{-1}.

2.3 | Management response and recommendations

Management tools at the disposal of decision-makers and farmers have been tested to mitigate drought in the U.S. Midwest. A. J. Lindsey and Thomison (2016) found that drought-tolerant hybrids resulted in a higher maximum yield with a lower agronomic optimum plant density relative to conventional hybrids if planted in the adequate window (May, Ohio). When planted late (June), the drought-tolerant hybrids generally resulted in lower maximum yield though agronomic optimum plant density also decreased.

Mineral nutrient management is a critical piece in the response of hybrids to drought (A. J. Lindsey et al., 2015; Ul-Allah et al., 2020). Due to the positive correlation between water and nutrient availability and uptake of nitrogen and potassium, the responses of corn to drought stress are influenced by these nutrients (Hatlitligil et al., 1984; K. I. Kim et al., 2008; Rudnick & Irmak, 2013; Schlemmer et al., 2005; Ul-Allah et al., 2020). Nitrogen and water availability interact, increasing their use efficiencies if adequate supply co-exists (Al-Kaisi & Yin, 2003). A. J. Lindsey et al. (2015) studied plant growth and grain yield response of four corn hybrids differing in drought tolerance and maturity to five sidedress N rates (between 0 and 270 kg N ha^{-1}) in four site years in Ohio. Their results showed that at the blister stage (R2, Abendroth et al., 2011), drought-tolerant AQUAmax hybrids were 3% taller, had 3% lower relative chlorophyll content, and had 5% lower ear-leaf N content relative to the conventional counterpart. Grain yield at both the agronomic and economic optimum N rates was similar regardless of hybrid. The authors suggested that these drought-tolerant hybrids can be managed using Ohio's current N rate recommendations, the same as are used for conventional hybrids. Ao, Russelle, Varga, et al. (2020) suggested that an Artesian hybrid in Minnesota may have a slightly greater N requirement than a standard hybrid as evidenced by higher yields when N applications were 50% over current recommended values. Future studies should evaluate other drought-tolerant hybrids (i.e., different genetics) across varying conditions to explore if different responses exist.

When water and N supply is insufficient (Figure 4a, crop displaying visual symptoms of deficit water stress vs. Figure 4b, crop lacking water deficit symptoms), a reduction in kernel number, kernel weight, dry matter, yield, and harvest index can be expected (Boomsma et al., 2009). The adequate supply of N improves corn productivity and water use due to increased canopy, which helps achieve more light interception and reduces soil water evaporation (Ogola et al., 2002). The water requirements in corn increase markedly after the V10 stage (10 collared leaves); from that point onward, limited water availability can negatively affect yield components by reducing kernel number and kernel weight (Campos et al., 2006; Ciampitti & Vyn, 2011). The highest water use in corn occurs around the late vegetative stages up to the early grain-filling period (Kranz et al., 2008; O. Ortez, Lindsey, et al., 2022). At this point in the crop cycle, drought stresses reduce yields due to reduced kernel numbers (Otegui et al., 1995).

If happening at pollination time, reported yield losses due to drought stress have included as much as 6.8% per day (Bruce et al., 2002). Increases in stress severity can result in larger yield losses per day (Çakir, 2004), relative to daily losses reported in previous studies. One possible management response to minimize drought and heat stress on corn is to vary planting dates and hybrid maturities in a season to induce variation in the flowering period (A. J. Lindsey & Thomison, 2016). Incurring some yield penalty in some fields as a sunk cost from delayed planting or using sub-optimal maturities may be warranted to reduce the risk of pollination failure in all fields in a given year. However, this decision is a preemptive management choice; knowing if high temperatures or drought would coincide with flowering and pollination stages is not possible at time with current weather prediction and phenological modeling tools. Reproductive resilience to drought has been identified as a greater contributor to drought tolerance in corn compared to root architecture (Messina et al., 2021), so it is possible choosing hybrids with differential traits for drought tolerance may also factor into hybrid selections prior to planting to ensure flowering synchrony.

Management strategies to increase water infiltration rates, water holding capacity, and reduce water loss from surface evaporation (Duiker, 2022) may help reduce the impact of short-term water deficit conditions but may have limited efficacy in the event longer term droughts occur. Conservation tillage has been largely recommended to achieve goals related to soil conservation, water management, and building soil organic matter which contribute to soil productivity and crop yield (Busari et al., 2015). In addition, practices aligned to reduced tillage (or no-till) are of interest due to carbon sequestration that has the potential to contribute to mitigation efforts on climate change (Manley et al., 2005). In a meta-analysis, DeFelice et al. (2006) reported yield advantages in no-till systems (relative to conventional tillage) in southern areas of the United States where warmer temperatures and low soil water holding capacities frequently happen. On the other hand, for the northern United States, the authors reported lower yields, and this was associated with colder and wetter spring conditions and poorly drained soils relative to the south.

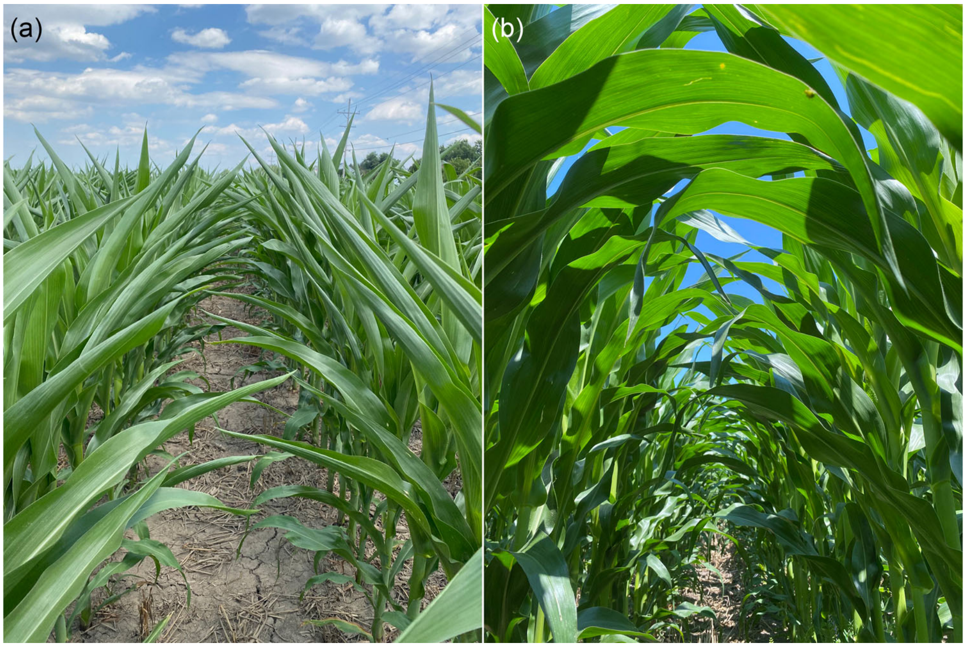

FIGURE 4 Two contrasting corn fields in northcentral Ohio at vegetative stages. (a) Drought and heat stress symptoms are visible in the plant canopy (leaf rolling and cracked soil). (b) healthy plant canopy with more light interception. Photos: Osler Ortez.

The use of controlled drainage structures may help retain water to facilitate off-season soil moisture recharge (Clevenger, 2020) and could raise the water table to help alleviate short-term water deficit conditions. For some limited areas in the U.S. Midwest (e.g., Kansas, Nebraska), irrigation (mainly pivot irrigation) has been a good strategy used; several factors are critical for efficient irrigation regimes and estimating crop water requirements in the field. These factors include crop and irrigation water productivity, seasonal basal crop coefficient, and crop evapotranspiration (Ao, Russelle, Feyereisen, et al., 2020). Studying a drought-tolerant and standard hybrid, Ao, Russelle, Feyereisen, et al. (2020) found that corn reached better physiological acclimation when drought exposure happened earlier in the season. Improvements to irrigation methods can be made to achieve better and higher crop and water use efficiencies (Djaman & Irmak, 2012; Hao et al., 2015; Panda et al., 2004). For example, conventional irrigation (water applied to reduce any yield loss or risk of water losses) tends to have lower water/crop efficiencies than deficit irrigation (limited irrigation, which reduces evaporation, runoff, and leaching) (Dietzel et al., 2016). A holistic understanding of crop water use during the season should be essential when breeding efforts and irrigation plans are developed (Bausch et al., 2011). It is known that the water requirement, hence the susceptibility to drought and stress, changes during the season. During the reproductive phase of corn, the kernel milk and dough stages (R3 and R4 stages, respectively) have a better benefit to water relative to later stages (Payero et al., 2009), indicating that higher water needs and susceptibility to drought occur earlier in the season rather than later. However, the intensity of evapotranspirative demand and drought conditions may still result in stress occurrence later in the grain-filling period.

A. J. Lindsey et al. (2018) studied morphological and physiological traits that may confer tolerance and plasticity to a drought-tolerant hybrid relative to a conventional hybrid under different plant densities and planting dates in six site years in Ohio. Despite favorable conditions for corn growth throughout their study, the drought-tolerant hybrid achieved a comparable or higher photosynthetic rate (8%–10% higher) with less stomatal conductance (22%–30% lower) relative to the conventional hybrid. Across the conditions studied, both hybrids had similar morphological and physiological responses to plant density and planting date. In other studies, Cooper et al. (2014) demonstrated that growing drought-sensitive and drought-tolerant hybrids at different plant densities resulted in different yield responses when grown in favorable environments and drought conditions. Furthermore, Messina, Ciampitti, et al. (2022) demonstrated that AQUAmax hybrids yielded more than non-AQUAmax counterparts under water deficit conditions; in these studies, the yield differences were dependent on plant density (six site years in the United States and Chile). Plant densities varied from 2.5 to 12.5 pl m^{-2}; higher plant densities (achieved with drought-tolerant hybrids) were associated with higher yields across severe water deficit and moderate water deficit scenarios. These authors concluded that the deliberate selection of hybrids for yield performance under water deficit was critical for the improvement of yield stability after two decades of drought breeding in corn.

Research results demonstrate that plant densities could affect the grain yield response of drought-tolerant versus standard hybrids under drought stress, depending on environments and growing conditions. Given the results from the various studies discussed in this section, when local conditions may be prompted by drought and heat stress, the use and adoption of drought-tolerant hybrids should be one of the primary management strategies to alleviate the potential threat and yield losses, albeit other strategies exist (e.g., efficient irrigation, adjusting planting dates or relative maturities, optimum planting densities, adequate nutrient supply).

2.4 | Future research needed

Further research is necessary to better understand the environmental stress of drought and heat in corn, more so with the rapidly raising concerns about warmer air temperatures and volatile precipitation availability. When conducting research in drought and heat stress, one of the limitations is how to isolate one effect from the other under field conditions since these conditions are often associated and results can be compounded by each other. Jeschke (2021a) reported that heat stress impact on corn production is likely a response to intensified water stress instead of the direct stress from heat alone. Another potential issue with past work is variance in the actual crop stage at the time of measurement or treatment implementation. Most studies discussed to date utilize a common planting date and may have some variance in the actual phenological stage being assessed when using a common measurement date for all hybrids. Varying planting date in corn with differing maturities has been used to ensure heat stress treatments were employed at the same phenological stage (Rattalino-Edreira & Otegui, 2012; Rattalino-Edreira et al., 2011) and could be one mechanism to utilize in future field experiments to better describe the effect of stress at different growth stages.

Studies in controlled conditions can alleviate some of those limitations and help to answer some fundamental questions that can later be scaled up to field conditions in separate scenarios, though corn production levels in controlled conditions have limitations relative to field scale scenarios. Installation of large rainout shelters (Snyder, 2018) may provide infrastructure to test hybrids or experimental hypotheses, though capital investments in installation, maintenance, and repair may have inhibited wider adoption of these. Others have utilized impermeable ground cover to exclude water infiltration from rain events (A. J. Lindsey et al., 2017) or deficit irrigation (Ao, Russelle, Varga, et al., 2020; Ao, Russelle, Feyereisen, et al., 2020), but manipulation of other atmospheric variables such as evapotranspiration and vapor pressure deficit are still major challenges. Infrastructure such as the free-air carbon dioxide enrichment sites at the University of Illinois does provide a more integrative opportunity to manipulate multiple variables at a given time (Ainsworth & Long, 2021), and expanding crop-centric locales to other states may be beneficial as heat and drought events may become more frequent in typical rain-fed environments.

The selection of drought-tolerant hybrids has been a relevant tool to mitigate crop losses when drought occurs (Cooper et al., 2014; A. J. Lindsey et al., 2018; Messina, Ciampitti, et al., 2022), which is more critical in areas where water is a limiting resource (and irrigation is not an option). With climate change and new weather patterns, more research will be necessary to update our understanding of drought-tolerant hybrid responses to the environment. Continued research on drought and heat stress during or close to pollination in corn seems to warrant more attention as that is when the greatest crop losses occur (due to more water demand).

Given some of the inconsistencies of hybrid comparison results outlined in the literature (drought-tolerant vs. standard hybrids), further research is needed to understand better the agronomic and physiological mechanisms that these undertake to achieve higher or better productivity and yields under different drought stress conditions, and some of the literature cited in this section provide excellent starting points. Studying how N and water requirements differ among these hybrid groups would enhance the understanding and potential future directions. Anecdotal evidence from Minnesota in 2021 suggested uniform and rapid emergence (achieved in fields with less surface residue and experiencing spring tillage) may have resulted in improved tolerance to drought later in the season over fields with heavy residue that were slower to emerge, though autumn surface residue is key to help dry soils regain moisture over the winter (Cates & DeJong-Hughes, 2022). Examining the effect of planting date, residue management, and emergence uniformity may be a target for future research.

Irrigation has been one of the strategies to mitigate drought in the western U.S. Midwest (e.g., Kansas, Nebraska), but water has become a scarcer resource (Falkenmark, 2013). Therefore, achieving better and higher crop and water use efficiencies in irrigated cropland is an important need (Djaman & Irmak, 2012; Hao et al., 2015; Panda et al., 2004). On the other hand, in regions without irrigation, efforts should aim to improve crop water use and productivity in order to keep up with high (or higher) crop yields as temperature and atmospheric vapor pressure deficit increase (DeLucia et al., 2019).

Other important research areas include the adoption of cover crops, when/if adopted properly, as potential strategies for drought mitigation. Cover crops can help by achieving better water infiltration levels (e.g., less water runoff) and better soil structure (Krupek et al., 2022) along with cooler temperatures in the soil (Yang et al., 2021a). Greater water productivity in the crop can be achieved if there is optimum water absorption in the soil and minimum water loss through soil evaporation or runoff. Along these lines, crop diversification (i.e., rotations) is another outstanding strategy to help mitigate drought. Crop diversification brings benefits in ways of different water and nutrient needs and residue composition left in the field after harvest. Farmers in areas with significant drought and heat concerns have included sorghum [*Sorghum bicolor* (L.) Moench], cowpea [*Vigna unguiculata* (L.) Walp.], and chickpea (*Cicer arientinum* L.) as regular rotational crops (e.g., western Midwest region); expanding rotations to include some of these crops in the eastern and northern Midwest may become a viable option as heat and drought increase. Broadly, the corn-soybean [*Glycine max* (L.) Merr.] rotation has remarkable benefits (Seifert et al., 2017); hence, this is a strong starting point for mitigation at least to some degree. As adverse weather events and long-term weather patterns such as heat and drought continue to affect corn production regions, more research in crop breeding and agronomy is needed to withstand and mitigate these conditions.

3 | SOLAR RADIATION

3.1 | Light interception and solar radiation importance for corn production

Solar radiation intercepted by the crop canopy is one of the most important factors that influences crop development (Loomis & Connor, 1992). Photosynthetically active radiation (PAR), which encompasses the spectral range of solar radiation required for photosynthesis (400 and 700 nm), is most important (Campillo et al., 2012). Solar radiation drives crop photosynthesis, the accumulation and movement of photosynthetic products, the formation of plant organs, transpiration, and crop yield (Campillo et al., 2012; Tollenaar et al., 2017; Y. Yang et al., 2019; Yang et al., 2021b). Previous research has determined that corn biomass production is directly proportional to the amount of solar radiation intercepted by the plant, and for a given harvest index, grain yield is directly proportional to the amount of biomass produced (Muchow et al., 1990). Both the total amount of available radiation and proportion of the available radiation intercepted by the crop are important drivers for corn yield (Muchow et al., 1990). Overall, in the absence of additional environmental stresses (e.g., drought, pest pressure, and nutrient deficiencies), previous research has shown a close and positive relationship between corn yield and the total amount of solar radiation intercepted by the crop (Jong et al., 1982; Loomis & Williams, 1963; Muchow et al., 1990; Tollenaar & Bruulsema, 1988). Improvement in radiation use efficiency over the last 100 years was 0.0049 g MJ^{-1} $year^{-1}$, which translates to a 3 g m^{-2} $year^{-1}$ increase in grain yield (Messina, Rotundo, et al., 2022). The most recent maximum shoot radiation use efficiency in corn was estimated to be 3.4–3.8 g MJ^{-1} PAR absorbed (Lindquist et al., 2005; Singer et al., 2011; Stöckle & Kemanian, 2009).

3.2 | Impact of short-term occlusion of light due to cloud cover and smoke, changes over time

Short-term changes to light availability can stem from dust storms, also known as haboobs (Ashford, 2022). The occurrence of wind erosion has been evident in the United States in recent memory since the Dust Bowl of the 1930s (spurring the founding of the Natural Resource Conservation Service) (Warrick, 1980), though these storms have been observed more recently in states such as Iowa, Kansas, Nebraska, Minnesota, and the Dakotas (Hauser & Jiménez, 2022). These events cause temporary reductions in light availability and tend to pass quickly, though they may leave dust deposits behind on plant tissue. Yield reductions from these events more likely stem from losses of leaf tissue, reductions in stand due to stalk breakage, or due to topsoil erosion (long-term impact on future yield); one source claimed that 6.7–26.9 Mg soil ha^{-1} were lost from South Dakota during the May 2022 dust storm (Gewin, 2022).

Plant-available solar radiation can be impacted by cloud cover, haziness, wildfire smoke, and increasing air pollution, which includes particulate matter such as sulfate and soot (Alados et al., 2000; Durand et al., 2021; Jeschke, 2021b; Liepert, 2002). This is particularly important for C4 crops (e.g., corn) due to a higher light saturation point in comparison to C3 crops (e.g., soybean), thus increasing crop susceptibility to reductions in solar radiation (Ehleringer et al., 1997; Jeschke, 2021b). Cloud cover and smoke caused by wildfires have the ability to absorb and reflect solar radiation, thus reducing the total amount available to plants (Alados et al., 2000; Jeschke, 2021b). For example, cloud cover has been shown to reflect 20% and absorb 3% of incoming solar energy from the sun (Campillo et al., 2012). In addition, Jeschke (2021b) observed 23%, 52%, and 62% reductions in PAR under partly cloudy, cloudy, and rain conditions, respectively, across four different summer days in Iowa. Although a single cloudy day is unlikely to influence corn yield, consecutive cloudy days have been shown to decrease corn yields. A daily solar radiation decrease of 46% over a period of seven consecutive cloudy days during the dough (R4) growth stage (August 19–25) in Nebraska resulted in a corn yield reduction of 5.2% in simulations (Elmore et al., 2019). Both the altitude and thickness of different cloud layers affect the total amount of solar radiation absorbed (Alados et al., 2000).

In comparison to cloud cover, wildfire smoke has been shown to reduce total solar radiation by 10%–30% over a 4-day period in California during peak smoke production periods (Juliano et al., 2022). In addition, Hemes et al. (2020) and Scordo et al. (2021) observed PAR reductions of 3.6% and 11% over summer periods of 58 and 55 days, respectively, from wildfire smoke in California. Furthermore, A. Lindsey et al. (2021) observed PAR reductions of 6%–7% in Ohio during June and July, which aligns with persistent wildfire smoke in the atmosphere (White et al., 2023) during this period. This trend suggests that increasing wildfire incidence in the western United States and Canada can impact Midwest corn production. Similar conditions occurred in June 2023 throughout much of the Midwestern United States (L. E. Lindsey et al., 2023; Quinn, 2023). Wildfire smoke can also increase ground-level ozone (O_3), which can harm plants by entering the stomata and oxidizing plant tissue during respiration, accelerating plant senescence, and inducing cell death (Jeschke, 2021b; McGrath et al., 2015).

In contrast to observed negative impacts, water vapor within clouds and wildfire smoke may also enhance photosynthesis by scattering incoming light and increasing incident diffuse radiation (Hemes et al., 2020). Gains in photosynthesis in corn leaves decrease (or are eliminated) at light intensities greater than 1500 μmol m^{-2} s^{-1} photosynthetic photon flux density (PPFD) (Usuda et al., 1985; Wareing et al., 1968); in the field, full sunlight can exceed PPFD of 2000 μmol m^{-2} s^{-1}, which is greater than the levels which plant can utilize most efficiently. Species with C4 photosynthetic pathways are also slower to adjust to fluctuating light intensity than C3 species (Y.-T. Li et al., 2021), so lower intensities of ambient sunlight may also facilitate faster recovery of photosynthetic activity following exposure to sunflecks. Diffuse radiation scatters and redistributes light throughout crop canopies, thus increasing light use efficiency and productivity (Hemes et al., 2020). For example, Hemes et al. (2020) observed a 2.5% increase in plant photosynthesis due to a 34% increase in diffuse radiation caused by wildfire smoke. However, this study only examined ecosystem productivity, not crop yield, and diffuse radiation impacts on plant growth are dependent on crop leaf area index, height, and canopy characteristics (Hemes et al., 2020). Others have also reported greater instantaneous canopy photosynthetic rates (Rochette et al., 1996) and radiation use efficiency (Rochette et al., 1996; Sinclair et al., 1992) under diffuse light (cloudy sky) conditions compared to direct light (clear sky).

Both cloud cover intensity and wildfire incidence have increased over time. Research has observed global declines in solar radiation ranging from 1.4% to 2.7% per decade due to climate warming (Che et al., 2005), small declines in global cloud cover (0.4% per decade) (Eastman & Warren, 2013), and increases in aerosol (soil dust, sulfates, black carbon, and organic matter) concentrations (J. Wang et al., 2009) due to increases in the intensity and frequency of large forest fires. Over the last 40 years, burned areas caused by wildfires in the United States have increased by 400% (National Interagency Fire Center, 2021), due to increased fuel load in forested areas and increased fuel dryness due to increasing temperatures and reduced precipitation caused by climate change (Burke et al., 2021). Therefore, as wildfire intensity and frequency are expected to increase, the release of solar radiation absorbing aerosols into the atmosphere is expected to increase. Furthermore, the total amount and proportion of visible radiation reaching crop canopies is expected to decrease in the long term due to climate change, resulting in negative impacts on plant photosynthesis (Spracklen et al., 2009; Yue & Unger, 2018).

It is also possible that reductions in intensity may be offset in part by daylength; Chang (1981) observed a stronger correlation between grain yield and daylength compared to daily radiation intensity. However, growing season solar radiation changes over time for the U.S. Midwest are less clear, with recent research suggesting solar radiation has increased over time in this region. From 1998 to 2020, total growing season (April–October) direct normal irradiance, diffuse horizontal irradiance, and global horizontal irradiance from central Indiana have changed by +16, −14, and −1%, respectively (National Solar Radiation Database, 2023). Furthermore, recent research by Tollenaar et al. (2017) suggests that solar brightening (decadal-scale increases in incident solar radiation) during the grain-filling phase of corn has contributed 27% to the U.S. Midwest yield trend increases from 1984 to 2013, yet the authors acknowledge future trends are uncertain.

3.3 | Impact of long-term reduced solar radiation on corn

Corn yield responses to varied solar radiation levels have been previously studied with shading experiments. Previous research has observed significant yield reductions caused by reduced solar radiation and has also observed negative linear relationships between solar radiation reduction and grain yield (Earley et al., 1966; Gao et al., 2017; Jong et al., 1982; Reed et al., 1988; Y. Yang et al., 2019). For example, Y. Yang et al. (2019) observed a >50% reduction in corn yield when solar radiation was reduced by 50% using a shade treatment, beginning at silking and lasting until maturity; as shading increased from 30% to 50%, yield reductions doubled. Similarly, Hashemi-Dezfouli and Herbert (1992) observed yield reductions from 23% to 66% with a 50% reduction in solar radiation using a shade treatment starting at 44 days after emergence and continuing through plant maturity. Yield reductions caused by reduced solar radiation are also dependent on the timing of solar radiation reductions during the corn growing season. W. Liu and Tollenaar (2009) observed corn grain yield reductions of 21%, 29%, and 23% for shading treatments implemented during pre-silking, silking, and post-silking, respectively. Moreover, Gao et al. (2017) observed yield reductions of 24% and 55% for pre-silking (6th leaf stage to tasseling) and post-silking (tasseling to physiological maturity), respectively, suggesting similar reductions in solar radiation have more impact on corn yield during the silking and grain-filling stages compared to during the vegetative growth stages (Jeschke, 2021b).

Corn yield reductions caused by solar radiation reductions have largely been attributed to reductions in plant photosynthetic rate (Moss & Musgrave, 1971), whole plant biomass (Andrade & Ferreiro, 1996; Gao et al., 2017; W. Liu & Tollenaar, 2009; Mbewe & Hunter, 1986; Y. Yang et al., 2019), root biomass (Gao et al., 2017; Guo et al., 2022), and overall plant assimilate supply (Reddy & Daynard, 1983). Mbewe and Hunter (1986) observed whole plant biomass reductions of 21%, 30%, and 27% for seasonal accumulated solar radiation reductions of 23%, 20%, and 24%, respectively. Similarly, Yang et al. (2021b) observed corn whole plant biomass reductions of 4.5%, 10.7%, and 20.2% for 15%, 30%, and 50% shade treatments, respectively. In addition, Guo et al. (2022) determined for every 100 MJ m^{-2} reduction (~17% reduction) in total intercepted PAR between the V3 stage and through plant maturity, corn root and shoot dry weight were reduced by 0.19 and 1.35 g m^{-2}, respectively. These reductions in corn photosynthetic rate, plant biomass, and assimilate supply, especially during silking and early grain filling, have caused delayed silking (Hashemi-Desfouli & Herbert, 1992; Mbewe & Hunter, 1986; Reed et al., 1988), reduced kernel number (Andrade, Echarte, et al., 2002; Earley et al., 1966; Hashemi-Dezfouli & Herbert, 1992; Kiniry & Ritchie, 1985; Reed et al., 1988), reduced kernel weight (Andrade & Ferreiro, 1996), kernel abortion (Reddy & Daynard, 1983), and increased incidence of ear barrenness (Hashemi-Desfouli & Herbert, 1992). In addition, reductions in solar radiation have also been shown to decrease lower stalk quality and increase the incidence of plant lodging due to reduced plant photosynthesis and greater stalk carbohydrate extraction (Y. Yang et al., 2020).

3.4 | Management considerations and future research

Solar radiation reduction impacts have been shown to vary by hybrid type and plant density. Y. Yang et al. (2019) observed a significant yield reduction (13%–15%) from one corn hybrid at a 15% solar radiation reduction, whereas the other hybrid did not reduce yield. Yang et al. (2021b) observed greater yield reductions and plant biomass reductions in one hybrid compared to another at multiple shading levels (15%–50%). Previous research has attributed corn hybrid tolerance differences to solar radiation reductions to hybrid plant density tolerance and weak-light stress performance (Stinson & Moss, 1960; Y. Yang et al., 2019). However, the differences in hybrid tolerances are still not entirely clear, especially in current genetics. Variable responses of yield due to shading may be more related to the plant growth rate during the critical period for kernel set (Andrade et al., 1999; Andrade, Echarte, et al., 2002). Reduced growth as a result of shading during this phase may be more detrimental than shading at other phases of growth and may be related in part to differences in traits such as corn hybrid maturity and manipulation of planting date. Optimization of light attenuation through the canopy may also help mitigate yield losses due to reduced solar radiation (Lacasa et al., 2022).

In addition to corn hybrid differences, G. Liu et al. (2021) observed a positive linear relationship between accumulated solar radiation and optimum plant density, suggesting solar radiation level could be matched to optimum plant density. For corn planted at higher population densities, PAR reductions can cause greater yield reductions compared to corn planted at lower population densities (Hashemi-Desfouli & Herbert, 1992). For example, Hashemi-Desfouli and Herbert (1992) observed a 23% corn yield reduction with shade (50% light reduction) at low plant densities, whereas at high plant densities, a 66% yield reduction with shade was observed, which suggests higher levels of canopy leaf shading associated with higher plant densities can potentially exacerbate yield impacts of reduced solar radiation. Andrade and Ferriero (1996) similarly documented a 22%–24% yield reduction with a 45% reduction in radiation. Furthermore, Wu et al. (2022) observed a 33% and 40% reduction in per plant maximum photosynthetic rates at a population density of 123,000 plants ha^{-1} compared to plants at population densities of 75,000 or 15,000 plants ha^{-1} using shade treatments. Burgess and Cardoso (2022) suggest targeting leaf canopy structure (i.e., leaf area, angle to affect light attenuation) in addition to greater tolerance to fluctuating light conditions to improve solar radiation capture. Y. Yang et al. (2019) determined corn yield losses caused by low solar radiation could be mitigated by targeting hybrids with low light tolerance and reducing plant densities. However, if solar radiation is non-limiting, corn plant densities can be increased to improve yield (Y. Yang et al., 2019). In corn, much of the light (80%–90%) is intercepted by the upper 50% of the canopy (X. Wang et al., 2008).

Andrade and Ferreiro (1996) observed a 0%–16% increase in yield when plots were thinned to double the light availability compared to the control. Intra-canopy lighting has been shown to increase corn yield by 54%–70% when supplementing with artificial fluorescent lights (Graham et al., 1972; Ottman & Welch, 1988) though is unlikely to be practical in field production environments. Optimization of canopy light absorption (Lacasa et al., 2022) and spatial arrangement of plants through altering row spacings and seeding rates may become more critical in time. Increasing uniformity of plant spacing with narrowing rows to 0.38 or 0.5 m spacing increased grain yield marginally (0%–5%) (Andrade, Calvino, et al., 2002; Widdicombe & Thelen, 2002; Nielsen, 1988); more recent reports suggest similar yield trends exist with more modern hybrids (Bayer Crop Sciences, 2022; Licht et al., 2019).

Overall, previous research suggests that corn hybrids with improved stay-green and photosynthetic efficiency characteristics planted at reduced plant densities can help mitigate reductions in solar radiation (Yang et al., 2021b). In addition, C4 plants (e.g., corn) do have the ability for short-term acclimation under low light intensity conditions through the regulation of the biochemical carbon concentrating mechanism, but this acclimation was not observed in intermediate or high light intensity conditions (Bellasario & Griffiths, 2014). Most of the research on solar radiation has been primarily performed in China or South America, within different environments and utilizing different hybrids than U.S. Midwest corn production. In addition, many of the previous studies are older and do not include current corn hybrids, suggesting future research with updated genetics is needed. Therefore, as solar radiation changes continue to persist, future research may need to address the impacts of corn hybrid types and optimum plant arrangements required to perform under these conditions.

4 | HEAT UNIT ACCUMULATION

4.1 | Changes in seasonal heat unit accumulation due to changing temperatures

One final long-term condition under consideration of this review is how heat unit accumulation during the growing season may impact corn growth and development. An increase in the mean annual non-frozen season of 0.189 day year^{-1} has been observed in the northern hemisphere (Y. Kim et al., 2012), mostly driven by an earlier onset of spring by 0.149 day year^{-1} though also the day of first freeze in the autumn has been occurring later, and autumn temperatures have remained higher (Abendroth et al., 2019). The frost-free thermal time in the Midwestern U.S. has been increasing by 0%–0.3% per year since 1950 (Abendroth et al., 2019), resulting in a 16-day increase in this period in the Great Lakes region (GLISA, 2017). Other researchers have predicted that these trends will continue shifting in these directions (Wubbles & Hayhoe, 2004). This shift toward a longer growing season provides corn growers, particularly in northern production systems, with an opportunity to increase yield and profits by selecting hybrids with later comparative relative maturity (CRM) or greater growing degree unit (GDU) requirements to achieve flowering and/or maturity (Parent et al., 2018).

Increasing in-season temperatures have also contributed to increased accumulated GDU totals; in most parts of the United States, average temperatures later in the season have increased by almost ∼1˚C over the last 50 years (Hatfield & Dold, 2018). A 1˚C increase in temperature in crop response models suggests that a 10% yield reduction could be experienced (Hatfield & Dold, 2018). Photorespiration, or the process of ribulose-1,5-bisphosphate carboxylase/oxygenase (RUBISCO) undergoing oxygenase activity instead of carboxylase activity resulting in CO_2 release instead of fixation, is attributed to up to 50% yield loss in C3 plants (South et al., 2018), and rising temperatures will increase the yield penalty (Cavanagh et al., 2022). Photorespiration in C4 plants like corn is minimized by concentrating CO_2 near the RUBISCO enzyme in bundle sheath cells (and reducing O_2 generation) (Edwards & Walker, 1983), so yield losses from photorespiration will be less than in C3 plants. Warm temperatures during the night will increase respiration rates and could negatively impact productivity (Chang, 1981). In Illinois, yield losses in corn of up to 40% were reported when night temperatures were elevated to 29˚C compared to ambient (18˚C) (Peters et al., 1971), though others estimate lower night respiration would only increase yield by ∼5% (Quin, 1981). In Argentina, respiration did not increase significantly when night temperatures increased by 5˚C from 1 week before to 3 weeks after silking (Cantarero et al., 1999), but the authors noted 8% more kernel abortion and attributed reduced kernel number to accelerated plant growth rates caused by higher temperatures.

Another concern with increasing temperatures is the effect on crop relative growth rate and how the daily radiation energy available per heat unit accumulated, also known as the photothermal quotient (PTQ), may be impacted. A greater PTQ during later vegetative stages is often favorable for yield (Veenstra et al., 2021) given more photons per heat unit effectively increase the leaf's potential for carbon reactions in photosynthesis. Achieving maturity in fewer calendar days due to higher temperatures would negatively affect the PTQ and may limit the number of days plants can absorb photons to conduct photosynthesis. Elmore et al. (2019) explored this using simulations for a 7-day period in Nebraska where light availability was reduced at the R4 stage, though expansion of this work to assess reductions at different developmental stages, occurrence as affected by planting dates, and hybrid CRM would help inform future agronomic practices like appropriate CRM selection for given planting dates. Research from both the Midwestern U.S. and Europe suggests that changes in seasonality could help improve yield in the future (Abendroth et al., 2019; Parent et al., 2018). Andrade, Echarte, et al. (2002) indicated plant growth rate was a major determinant of kernel set, so the impact on the yield of changes in PTQ may coincide with susceptible phenological stages more than calendar dates.

4.2 | Rate of heat unit accumulation and corn development

When the last spring frost occurs early, it gives time for soils to warm up so crop planting can proceed with a lower risk of poor or delayed seedling emergence. As soils warm up and early planting becomes feasible, growers can use mid- or late-maturing hybrids with extended grain-filling periods to achieve greater grain yield. Studies have shown each additional day of earlier planting contributes about 0.06–0.14 Mg ha^{-1} to yield increase (Long et al., 2017). Previous research indicates that there might be benefits from adjusting CRM selection based on planting date, but the interaction between planting date and CRM is variable across environments (Baum et al., 2019; Kratochvil et al., 2005; Tsimba et al., 2013b). However, there is a lack of regional research on this aspect, especially in northern corn production environments where growers can maximize the utilization of relatively short growing seasons by matching optimal CRM with planting date.

Corn typically requires approximately 45–58 GDUs (base 10˚C) to produce a newly emerged collared leaf to V10, lowering to 31˚C day leaf^{-1} after V10 (Abendroth et al., 2011; dos Santos et al., 2022). These developmental requirements have also changed over time as hybrids released in 2020 were able to produce new leaves 3%–9% more rapidly from V10 to tasseling than hybrids released in 1983 (dos Santos et al., 2023). The rate of GDU accumulation and corresponding phenological stages can also change with management decisions, seasonal conditions, and planting date especially prior to V6 (Bollero et al., 1996). Nemergut et al. (2021) reported lower daily soil GDU accumulation at 76-mm planting depth compared to shallower depths, and this resulted in a later calendar date of emergence and a partial developmental delay (V3.3) compared to shallower planting depths (V3.4) 3 weeks after planting. Corn achieved the V5 or V6 stage in 0%–40% fewer soil GDUs when soil temperatures were lower due to manipulation of soil temperatures with buried heating or cooling elements or from increased surface residue compared to warmer soils or soils with less residue cover (Bollero et al., 1996; Fortin et al., 1994; Swan et al., 1987). However, Swan et al. (1987) for the same trial reported 0%–25% more air GDUs required to achieve the V6 growth stage with heavy residue cover due to slower daily accumulation of soil GDUs compared to air GDUs (the ratio of soil GDU to air GDU < 1).

This discrepancy in early vegetative growth likely contributed to why more air GDUs to achieve silking and slower relative growth rates were reported under no-tillage (Azooz et al., 1995; Imholte & Carter, 1987). After V6, air temperature is the primary driver affecting leaf production (Swan et al., 1987). Plant phyllochron prior to V10 was positively correlated with radiation levels, and photoperiod was positively correlated with total leaf number and days to flowering (dos Santos et al., 2022); this may be in part because canopy temperature is closely correlated with direct irradiance (Knapp & Fay, 1997) and could result in a greater relative growth rate for irradiated plants. However, the importance of day length on phenology may be less important for temperate hybrids in the U.S. Midwest compared to tropical hybrids (Bonhomme et al., 1994; Chen et al., 2015).

Another challenge with using GDUs to quantify phenological development is that the daily rate of accumulation can also affect how quickly growth stages are achieved in corn. Plants grown at a daily temperature of 28˚C produced leaves three times more quickly than plants grown at a 16˚C daily temperature (Hardacre & Turnbull, 1986). This is evident when the average daily GDU rate was plotted (*x* axis) against total GDUs to achieve the identified growth stage (*y* axis) (Figure 5). Both Gilmore and Rogers (1958) and Imholte and Carter (1987) suggested that there were slight decreases in total GDUs required to achieve silking regardless of the rate of daily GDU accumulation though slopes were nonsignificant ($p > 0.17$).

Corn phenological progression through the reproductive stages varies considerably, taking approximately 110 GDUs from R1 to R3 and 67 GDUs from R3 to R5 (Abendroth et al., 2011). Research from Iowa does suggest that a minimum of 648˚C day during grain filling is needed to maximize yield (Baum et al., 2019). Swan et al. (1987) and Imholte and Carter (1987) found a decline in corn yield in years with insufficient GDU accumulation. Compression of GDU requirements to reach maturity has been observed with hybrids planted later in the season compared to the same hybrid planted under optimal time (Nielsen et al., 2002). Research from Indiana, Michigan, and Ohio reported that GDU requirements from planting to kernel black layer decreased by 3–4 GDU per day of delayed planting after May 1 (Agyei et al., 2022; Nielsen et al., 2002), though was not consistent across all environments. This GDU compression would suggest that growers could plant their usual hybrid maturities later than otherwise expected with minimal risk of late-season frost damage. It is possible that delayed planting could increase light penetration to the ear and result in greater direct illumination of tissues and higher temperatures during grain filling, but delayed planting consistently has less of an impact on light interception and plant height compared to seeding rate (A. J. Lindsey et al., 2018; Van Roekel & Coulter, 2011). However, during the severely delayed 2019 growing season, GDU compression was not evident in experimental data or observed by Michigan and Indiana growers (Nielsen, 2019) and even in the 2020 season in Ohio (A. J. Lindsey, 2020). Recent research in Michigan has shown that GDU compression magnitude depends on hybrid maturity and growing season (Agyei et al., 2022). Early-planted fields required more heat unit accumulation (or GDU elongation) to achieve growth stages

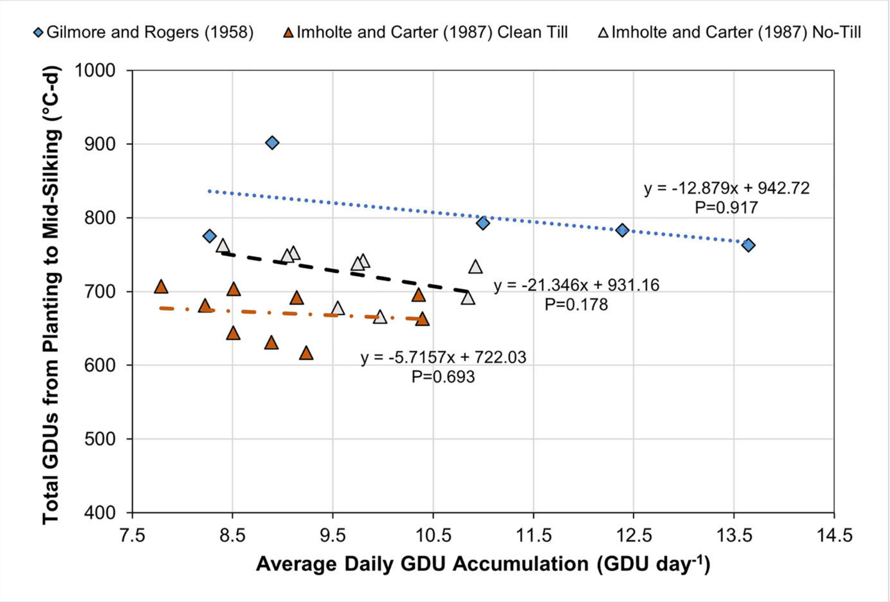

FIGURE 5 Total accumulated air temperature greater growing degree units (GDUs) from planting to silking as affected by daily GDU accumulation rates. Data were extracted from reported publications, with reported means used to apply simple linear regression for analysis using the REG procedure in SAS 9.4.

than predicted if planted at normal times (rather than experiencing compression phenomena). Research is needed to better understand and verify GDU requirement across corn hybrids of varying maturities and quantify its magnitude.

Rapid accumulation of heat units also has the potential to accelerate kernel development resulting in a shorter grain-filling period. It is unclear how this would also affect carbohydrate and nutrient remobilization during senescence in corn. Plants containing stay-green traits were able to maintain photosynthetic rates longer than plants lacking stay-green traits (Céline, 2019; Sekhon et al., 2019), which may allow grain filling to continue even as plants approach maturity. Corn physiological maturity and black layer development are shown to occur in response to reduced sucrose availability later in the season (Afuakwa et al., 1984) due to leaf senescence and cooler temperatures. Warmer than normal temperatures (e.g., September 2019) might result in increased sucrose availability and a delay in the development of the kernel black layer. Pre-mature senescence of leaves due to foliar diseases might play a role in these dynamics as well. Cloudy conditions during the grain-filling phase or low soil moisture during grain filling can slow this process and extend phenology including maturity and eventually grain dry down. Further work exploring this interaction of heat unit accumulation, light availability and interception, senescence, and yield is needed to better understand how these weather patterns interact to influence yield.

Field dry-down estimates are typically based on the Henderson Perry methodology (Henderson & Perry, 1966), and this methodology was recently modified by Martinez-Feria et al. (2019). Impacts of daily weather including recent and future trends in climate need to be included in dry-down algorithms and rigorously tested and evaluated with observation from field studies across various geographical regions. Delayed harvest, especially in late-maturity hybrids, can also lead to an increased risk of late-season foliar diseases (e.g., tar spot), frost damage, and mycotoxin contamination. The impacts of various environmental factors on corn phenological development and yield are not well understood and need further investigation. Understanding these dynamics is important for long-term yield predictions and necessary for the deployment of sound management decisions.

4.3 | Management considerations

A longer growing season would give farmers the opportunity to increase crop diversity in their fields. Crop diversity can be achieved by incorporating more cash crops (e.g., double cropping and winter annuals) or by the addition of cover crops in a crop rotation from an early autumn harvest date (L. E. Lindsey et al., 2023; Mohammed et al., 2023; Shrestha et al., 2021). High-yielding early-season CRM selections may enable farmers to utilize fall-planted cover crops or cash crops more easily and may also accommodate using corn as a double crop after a winter annual (A. J. Lindsey et al., 2020). Increasing crop diversity helps to break pest and disease cycles, reduces nutrient depletion, increases soil organic matter, and improves overall soil health. Avoidance of stressful periods (cool wet, hot-dry during flowering) may in part be achieved through the utilization of additional crops in these production systems.

The relationship between CRM and yield has been reported often in past work (Kratochvil et al., 2005; A. J. Lindsey & Thomison, 2016; Long et al., 2017; Tsimba et al., 2013b), usually observing yield increases with lengthening CRM values. However, selecting hybrids with CRMs with GDU requirements that equal or exceed what the growing season can supply may also result in a reduction in yield (Djaman et al., 2020) especially when unfavorable growth conditions exist (e.g., early frost damage in the autumn and delayed flowering time coinciding with high heat and water deficit conditions). Abendroth et al. (2021) reported that many producers outside of northern U.S. states reduced their hybrid CRM selection over 17 years rather than selecting longer maturities in response to lengthening growing seasons. This trend may have been in response to the increase in intense precipitation events. Heavy precipitation events, defined as the amount of precipitation falling in the heaviest 1% of storms, have increased by 35% between 1951 and 2017 in the Great Lakes region (GLISA, 2017). This seasonality of precipitation may result in excess water when not needed and limited water during critical crop growth periods. It also may not allow for crop planting (even though temperatures are appropriate) due to adverse soil moisture conditions. Other considerations that may also affect earlier planting could include delays to field preparation activities such as herbicide application, fertilizer application, cover crop management, or tillage procedures.

4.4 | Challenges in predicting phenology based on heat unit accumulation

Making decisions about appropriate hybrid maturity requires an accurate characterization of the growing season requirement of corn hybrids. Increasing temperatures have been predicted to negatively impact on crop yields; however, higher temperatures also mean plants could experience greater seasonal GDUs and exhibit faster relative growth rates than if lower temperatures were experienced. Accelerated growth rates may help offset the inability to plant early due to poor field conditions and still justify the expansion of CRM choices. In general, growers must balance the benefits of potentially higher yields associated with long CRM hybrids with the risks of later maturity dates, greater probabilities of killing freezes, and generally higher grain moisture even if the crop does reach maturity (Baum et al., 2019; Lauer et al., 1999; Tsimba et al., 2013a). The commonly used days-to-maturity system (CRM) by seed companies does not refer to finite calendar time (Nielsen, 2012) and lacks predictive accuracy in determining safe maturity in late planting situations and may have limited utility for making decisions about switching hybrid maturity. Assigning a CRM value for a hybrid often occurs by assessing the maturation of new hybrids to "check" hybrids with known maturation values, though the check hybrids used in trials may change over time. The relative values may also have contributed to a drift in actual maturity lengths of hybrids over the years (i.e., a 105-day CRM hybrid from 1980 would have a different value if assessed in 2020). Characterizing phenological milestones of flowering and maturity to GDU accumulation may help reduce this issue (Abendroth et al., 2021), though it is unclear how common it is for this information to be available from companies for genetic material. Additionally, GDU ratings have been determined based on optimal planting times, and the relationship between GDU and crop phenology may shift under delayed planting conditions. Studies that examine hybrids released in different eras in common-garden experiments could also be limited if arranged solely by relative maturity value rather than by GDUs to achieve phenological milestones (Badu-Apraku et al., 2017; O'Neill et al., 2004). This may be less problematic when large hybrid datasets are analyzed as the contribution of GDU drift for a CRM value would be minimized by having multiple CRM groups represented annually (Abendroth et al., 2021; Assefa et al., 2016).

Improving phenological models' accuracy is important to ensure accurate implementation of farming activities and accurate predictions of the agricultural future in response to changing environmental factors like CO_2 and temperature (Fu et al., 2020). Current phenology prediction tools (e.g., U2U: https://mygeohub.org/groups/u2u/purdue_gdd) do not account for GDU compression; this may be an artifact of GDU accumulation during kernel set and grain filling not accurately reflecting the temperatures experienced by the plant inside the canopy. There is clear evidence that soil management practices (i.e., residue retention and tillage) and planting decisions (planting date and depth) can affect the early-season growth rate. It is also unclear what role stay-green traits play in late-season grain filling and phenological progression. Field data are needed to update such tools so that they can better predict corn phenology in the face of current and future climatic conditions.

Farmers are increasingly adopting data management platforms to collate operational data that also include real-time information related to crop progress based on input data such as CRM and planting date. Farm size is increasing, and the workforce is declining, which may result in farmers relying on these tools to time critical field operations rather than on traditional scouting methods and in-person field checks. Inaccurate timing of management practices such as fertilizer application, fungicide applications, and harvest could result in substantial agronomic and economic losses. The inclusion of relative maturity or phenological development time points is required for some modeling programs (Anapalli et al., 2005; Bassu et al., 2014; Baum et al., 2020). Long-range predictions

TABLE 1 Summary of current management options to address long-term weather stresses and challenges associated with their implementation in the present and future. Areas of future work for each strategy are also outlined.

Stress source	Key reference(s)	Management response	Challenges	Future research
1. Drought and heat stress	Ao, Russelle, Varga, et al. (2020); Kansas Department of Agriculture (2013); Li et al. (2020)	Higher yields of drought-tolerant hybrid under drought stress before pollination and up to physiological maturity relative to standard hybrids have been reported.	Widespread drought in 2012 decreased rainfed corn yields; the western United States in particular was drastically affected.	Response of modern hybrids (newer releases) may not follow what past research has documented. Current weather conditions are different from those in the past.
	Andrade et al. (1999); Andrade, Echarte, et al. (2002)	Minimize the occurrence of stress during the kernel set period to optimize plant growth rate and ensure kernel numbers are preserved through varying hybrid CRM.	Unclear when stress occurrence will appear within a season, and the critical period (1 week before to 3 weeks after silking) is long.	Studying mechanisms to lower stress post-silking in field environments through management is key to preserving yield.
	Cooper et al. (2014); Messina, Ciampitti, et al. (2022); Roth et al. (2013); A. J. Lindsey et al. (2015); Ciampitti et al. (2015); A. J. Lindsey and Thomison (2016); Ao, Russelle, Varga, et al. (2020); Ao, Russelle, Feyereisen, et al. (2020)	Drought-tolerant hybrids produced a 1.0–3.0 Mg ha^{-1} yield increase relative to a drought-sensitive (standard) hybrid if drought conditions were present. Drought-tolerant hybrids had 0.3–1.0 Mg ha^{-1} lower yield relative to the standard hybrids when both hybrids were grown under well-watered conditions.	Higher yields for drought-tolerant hybrids have not been consistent or have been even negative. Yield advantages of drought-tolerant inconsistencies have been in part attributed to different environmental yield levels.	Studying drought stress and hybrid response in segmented yield levels can offer new insights. Further studies of varying plant densities response to heat and drought are necessary using current (newer) genetics.
	Busari et al. (2015); Manley et al. (2005); DeFelice et al. (2006)	Conservation tillage has been largely recommended for goals related to soil conservation, water management, and building soil organic matter which are all critical aspects of crop production.	Yield advantages have been reported in no-till systems (relative to conventional tillage) in southern areas of the United States. Lower yields have been reported in no-till systems in northern United States, and are attributed to colder and wetter spring conditions and poorly drained soils.	Spatial and temporal variability effects of tillage systems and how these affect corn response to heat and drought stress conditions.
	Ao, Russelle, Feyereisen, et al. (2020)	For the western U.S. Midwest (e.g., Kansas, Nebraska), irrigation (mainly pivot irrigation) has been a key strategy to produce high corn yields.	Several factors are critical for efficient irrigation regimes and estimating crop water requirements in the field. Irrigation system's approaches can be improved.	Research on crop and irrigation water productivity, seasonal basal crop coefficient, and crop evapotranspiration are important to maintain or improve corn yields under irrigation systems.
	Clevenger (2020)	The use of controlled drainage structures may help retain water to facilitate off-season soil moisture recharge and could raise the water table to help alleviate short-term water deficit conditions.	The cost, investment, and durability of these structures. Variability in efficacy is implicit as there are years when sub-surface drainage would be useful to improve crop growth and years when it is less useful.	Leverage research in areas where drainage structures are already in place, potentially on-farm research. For instance, farming operations in Northwest Ohio rely on drainage structures given the nature of soils and conditions.

(Continues)

TABLE 1 (Continued)

Stress source	Key reference(s)	Management response	Challenges	Future research
2. Solar radiation	Gewin (2022); Hauser and Jimenez (2022)	Increase conservation tillage practices to reduce soil erosion and conditions suitable for dust storms.	Tillage or field activities that generate dust may be necessary for other agronomic purposes.	Study duration of short-term occlusions on corn growth and yield at various growth stages.
	Chang (1981)	Look to leverage daylength to maintain or improve grain yield under reduced intensity conditions by planting earlier.	Conditions may not be suitable to accommodate early planting.	Assess planting date, daylength, and in-season available radiation impact on grain yield. Target solar radiation reductions at various growth stages to characterize predicted yield losses.
	Stinson and Moss (1960); Earley et al. (1966); Y. Yang et al. (2019); Yang et al. (2021b)	Hybrid tolerance to reduced solar radiation varies.	Unclear tolerance levels in modern hybrids grown in the Midwestern United States.	Future evaluation of current and future hybrid genetics for low radiation tolerance.
	Hashemi-Desfouli and Herbert (1992); Wu et al. (2022); Y. Yang et al. (2019); Andrade, Calvino, et al. (2002); Widdicombe and Thelen (2002); Nielsen (1988)	Adjust plant densities or plant arrangements to facilitate greater light penetration into canopies.	Changes in density need to be applied prior to stress occurrence and may be different from optimum under adequate light.	Target plant arrangement and densities in the field for hybrids exhibiting diversity in canopy structure.
3. Heat unit accumulation	Abendroth et al. (2019); Abendroth et al. (2021); Mohammed et al. (2023); A. J. Lindsey et al. (2020); Parent et al. (2018)	Adjust chosen CRMs to leverage longer seasons or pursue novel rotational practices.	Wet weather may prevent leveraging full season. PTQ influences the rate of phenological development and yield potential. Inconsistencies in CRM ratings exist within the industry. Finding new markets may affect rotational crop expansion.	Re-assess current planting recommendations. Standardize the approach to quantifying crop phenological characterization. Explore the feasibility of new cropping sequences.
	Bollero et al. (1996); Imholte and Carter (1987); Swan et al. (1987); Nemergut et al. (2021)	Anticipate that soil management practices can affect the speed of early-season development through the V6 stage.	Soil or water conservation practices may impact corn growth rates. Soil drying may further be delayed by residue retention resulting in the need to adjust CRM.	Standardize data collection or reporting to include consistent phenological metrics (i.e., calendar days, soil GDUs, air GDUs) allowing for improved phenological studies and modeling efforts in the future.
	Nielsen et al. (2002); Agyei et al. (2022)	Adjust CRM to account for planting date, though shift in maturity may be affected by GDU compression or elongation during grain filling.	May limit the grain-filling period and affect dry down period and late-season disease pressure.	Characterize environmental factors contributing to compression and elongation phenomena.
	Fu et al. (2020); dos Santos et al. (2022); Kumudini et al. (2014); Wang et al. (2018); Zhang et al. (2022)	Validate digital platform estimates of crop phenology with scouting and field checks.	Phenological modeling can help, but improvements need to be made to ensure effective and proactive management strategies are employed. Phenological development may vary from what is predicted in current management tools.	Evaluate the accuracy of digital platforms to predict crop stage to improve management efficiency. Improve crop phenological models to ensure accurate predictions can be made.

Abbreviations: CRM, comparative relative maturity; GDU, greater growing degree unit; PTQ, photothermal quotient.

that inaccurately characterize crop development and yield implications could lead to inaccurate climatic projections (and policies enacted in response to the models), resulting in future issues of food scarcity and security.

4.5 | Future research needs

Trends in climate change are highly variable in terms of geography; hence, a regional approach is needed to examine their impact on agricultural production and management strategies needed to maintain profitable crop production. One possible area to target is to develop a method to consistently quantify CRM values across genotypes to ensure accurate hybrid maturity classifications are made across seed sources.

Phenological prediction has been identified as a key bottleneck in global climate change models (Fu et al., 2020). Improving accuracy is key to ensuring scientific conclusions, and policy decisions are sound as temperature, heat unit accumulation, precipitation, light availability, and geography can affect growth and development. Efforts to improve these models are currently ongoing (Kumudini et al., 2014; dos Santos et al., 2022; N. Wang et al., 2018; Zhang et al., 2022), though increasing field studies in parallel with modeling work could be an area to help address discrepancies between current models and ground truth data. Utilization of aerial or satellite imagery in data management platforms to quantify near real-time vegetation values may reduce the need for accurate phenological prediction at the farm level. However, this information may still result in reactive management strategies and would limit the ability to predict future management needs with the current tools.

Continued work to investigate optimized relative maturity selections within geographies is needed to leverage seasonal increases in temperature, though considerations for management practices need to be expanded to inform these decisions. Choices relating to tillage practices, residue management, or cover crop use may affect appropriate CRM decisions and should be considered during hybrid selection. Incorporation of novel rotational cropping practices (e.g., double cropping and use of green manures) may also play a role in more fully leveraging the longer season while minimizing challenges associated with wet spring environments. The inclusion of rotational crops such as winter annual small grains or oilseeds may expand farmer options in the event wet spring conditions consistently limit early planting.

5 | CONCLUSIONS

Long-term weather patterns have the potential to affect corn growth, development, and yield. Periods of high heat and water deficit as well as limited light availability (e.g., quantity and quality) challenge the ability to maximize yield production in corn. Weather patterns affecting heat unit accumulation throughout the season can also affect grain yield and maturation rates and cause challenges for predicting crop phenological development. Current recommended practices to address the three long-term stress conditions described within this review and challenges associated with those management recommendations are summarized in Table 1. Advances in corn breeding and genetics, hybrid selection, and agronomic management practices are key to ensuring long-range corn productivity and fully leveraging possible benefits from the shifts in long-range weather patterns. Increasing season length (frost-free period) and diffuse light conditions may lead to improved yields for C4 crops such as corn. Optimizing hybrid selection (e.g., drought tolerance and maturity selections to leverage longer seasons) for improved yields is critical, though broader scale cropping system changes (i.e., crop rotations, increasing double crop practices, and use of cover crops) may also improve resiliency to long-term weather stress. Future efforts should focus on better understanding drought, heat, light availability, and GDU accumulation in corn under current conditions (e.g., weather, genetics, and management). Efforts to incorporate ground truth data on GDU compression or elongation as a result of seasonal weather changes should continue or be expanded to better inform models for climate change and crop development to improve their predictive ability.

AUTHOR CONTRIBUTIONS

Osler A. Ortez: Conceptualization; data curation; project administration; visualization; writing—original draft; writing—review and editing. **Alexander J. Lindsey**: Conceptualization; data curation; project administration; visualization; writing—original draft; writing—review and editing. **Peter R. Thomison**: Conceptualization; writing—review and editing. **Jeffrey A. Coulter**: Data curation; writing—original draft; writing—review and editing. **Maninder Pal Singh**: Conceptualization; data curation; writing—original draft; writing—review and editing. **Daniela R. Carrijo**: Writing—review and editing. **Daniel J. Quinn**: Conceptualization; data curation; formal analysis; writing—original draft; writing—review and editing. **Mark A. Licht**: Conceptualization; Data curation; Writing—original draft; Writing—review and editing. **Leonardo Bastos**: Visualization; Writing—review and editing.

ACKNOWLEDGMENTS

The authors would like to thank Paul Carter and Roger Elmore for their assistance in brainstorming ideas for the structure of this manuscript.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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REFERENCES

Abendroth, L. J., Miguez, F. E., Catellano, M. J., Carter, P. R., Messina, C. D., Dixon, P. M., & Hatfield, J. L. (2021). Lengthening of maize maturity time is not a widespread climate change adaptation strategy in the US Midwest. *Global Change Biology*, *27*, 2426–2440. https://doi.org/10.1111/gcb.15565

Abendroth, L. J., Elmore, R. W., Boyer, M. J., & Marlay, S. K. (2011). *Corn growth and development. PMR 1009*. Iowa State University Extension. https://store.extension.iastate.edu/product/Corn-Growth-and-Development

Abendroth, L. J., Miquez, F. E., Catellano, M. J., & Hatfield, J. L. (2019). Climate warming trends in the U.S. Midwest using four thermal models. *Agronomy Journal*, *111*, 3230–3243. https://doi.org/10.2134/agronj2019.02.0118

Adee, E., Roozeboom, K., Balboa, G. R., Schlegel, A., & Ciampitti, I. A. (2016). Drought-tolerant corn hybrids yield more in drought-stressed environments with no penalty in non-stressed environments. *Frontiers in Plant Science*, *7*, 1534. https://doi.org/10.3389/fpls.2016.01534

Afuakwa, J. J., Crookston, R. K., & Jones, R. J. (1984). Effect of temperature and sucrose availability on kernel black layer development in maize. *Crop Science*, *24*, 285–288. https://doi.org/10.2135/cropsci1984.0011183x002400020018x

Agyei, B., Andresen, J., & Singh, M. (2022). *Matching corn hybrid maturity to planting time for optimizing yield and dry down*. American Society of Agronomy Annual Meeting, Baltimore, MD, USA. https://scisoc.confex.com/scisoc/2022am/meetingapp.cgi/Paper/142864

Ainsworth, E. A., & Long, S. P. (2021). 30 Years of free-air carbon dioxide enrichment (FACE): What have we learned about future crop productivity and its potential for adaptation? *Global Change Biology*, *27*, 27–49. https://doi.org/10.1111/gcb.15375

Alados, I., Olmo, F. J., Foyo-Moreno, I., & Alados-Arboledas, L. (2000). Estimation of photosynthetically active radiation under cloudy conditions. *Agricultural and Forest Meteorology*, *102*(1), 39–50. https://doi.org/10.1016/S0168-1923(00)00091-5

Al-Kaisi, M. M., & Yin, X. (2003). Effects of nitrogen rate, irrigation rate, and plant population on corn yield and water use efficiency. *Agronomy Journal*, *95*, 1475–1482. https://doi.org/10.2134/agronj2003.1475

Anandhi, A. (2016). Growing degree days—Ecosystem indicator for changing diurnal temperatures and their impact on corn growth stages in Kansas. *Ecological Indicators*, *61*(2), 149–158. https://doi.org/10.1016/j.ecolind.2015.08.023

Anapalli, S., Ma, L., Nielsen, D. C., Vigil, M. F., & Ahuja, L. R. (2005). Simulating planting date effects on corn production using RZWQM and CERES-Maize models. *Agronomy Journal*, *97*, 58–71. https://doi.org/10.2134/agronj2005.0058

Andrade, F. H., Calvino, P., Cirilo, A., & Barbieri, P. (2002). Yield responses to narrow rows depend on increased radiation interception. *Agronomy Journal*, *94*, 975–980. https://doi.org/10.2134/agronj2002.9750

Andrade, F. H., Echarte, L., Maggiora, A. D., & Casanovas, M. (2002). Kernel number prediction in maize under nitrogen or water stress. *Crop Science*, *42*, 1173–1179. https://doi.org/10.2135/cropsci2002.1173

Andrade, F. H., & Ferreiro, M. A. (1996). Reproductive growth of maize, sunflower and soybean at different source levels during grain filling. *Field Crops Research*, *48*, 155–165. https://doi.org/10.1016/S0378-4290(96)01017-9

Andrade, F. H., Vega, C., Uhart, S., Cirilo, A., Cantarero, M., & Valentinuz, O. (1999). Kernel number determination in maize. *Crop Science*, *39*, 453–459. https://doi.org/10.2135/cropsci1999.0011183x0039000200026x

Angel, J. R., Widhalm, M., Todey, D., Massey, R., & Biehl, L. (2017). The U2U Corn Growing Degree Day tool: Tracking corn growth across the US Corn Belt. *Climate Risk Management*, *15*, 73–81. https://doi.org/10.1016/j.crm.2016.10.002

Ao, S., Russelle, M. P., Feyereisen, G. W., Varga, T., & Coulter, J. A. (2020). Maize hybrid response to sustained moderate drought stress reveals clues for improved management. *Agronomy*, *2020*(10), 1374. https://doi.org/10.3390/agronomy10091374

Ao, S., Russelle, M. P., Varga, T., Feyereisen, G. W., & Coulter, J. A. (2020). Drought tolerance in maize is influenced by timing of drought stress initiation. *Crop Science*, *60*, 1591–1606. https://doi.org/10.1002/csc2.20108

Ashford, M. (2022). Rare haboob of blowing dust leads to blackout conditions in parts of Nebraska. *Lincoln Star Journal*, https://journalstar.com/weather/rare-haboob-of-blowing-dust-leads-to-blackout-conditions-in-parts-of-nebraska/article_f71e176b-4816-509b-9e58-f4aa660ba0fd.html

Assefa, Y., Prasad, P. V. V., Carter, P., Hinds, M., Bhalla, G., Schon, R., Jeschke, M., Paszkiewicz, S., & Ciampitti, I. A. (2016). Yield responses to planting density for US modern corn hybrids: A synthesis-analysis. *Crop Science*, *56*, 2802–2817. https://doi.org/10.2135/cropsci2016.04.0215

Azooz, R. H., Lowery, B., & Daniel, T. C. (1995). Tillage and residue management influence on corn growth. *Soil and Tillage Research*, *33*, 215–227. https://doi.org/10.1016/0167-1987(94)00438-K

Badu-Apraku, B., Yallou, C. G., Obeng-Antwi, K., Alidu, H., Talabi, A. O., Annor, B., Oyekunle, M., Akaogu, I. C., & Aderounmu, M. (2017). Yield gains in extra-early maize cultivars of three breeding eras under multiple environments. *Agronomy Journal*, *109*, 418–431. https://doi.org/10.2134/agronj2016.10.0566

Bänziger, M., Setimela, P. S., Hodson, D., & Vivek, B. (2006). Breeding for improved abiotic stress tolerance in maize adapted to southern Africa. *Agricultural Water Management*, *80*, 212–224. https://doi.org/10.1016/j.agwat.2005.07.014

Barnabás, B., Jäger, K., & Fehér, A. (2008). The effect of drought and heat stress on reproductive processes in cereals. *Plant, Cell & Environment*, *31*, 11–38. https://doi.org/10.1111/j.1365-3040.2007.01727.x

Bassu, S., Brisson, N., Durand, J.-L., Boote, K., Lizaso, J., Jones, J. W., Rosenzweig, C., Ruane, A. C., Adam, M., Baron, C., Basso, B., Biernath, C., Boogaard, H., Conijin, S., Corbeels, M., Deryng, D., De Sanctis, G., Gayler, S., Grassini, P., … Waha, K. (2014). How do various maize crop models vary in their responses to climate change factors? *Global Change Biology*, *20*, 2301–2320. https://doi.org/10.1111/gcb.12520

Baum, M. E., Archontoulis, S. V., & Licht, M. A. (2019). Planting date, hybrid maturity, and weather effects on maize yield and crop stage. *Agronomy Journal*, *111*, 303–313. https://doi.org/10.2134/agronj2018.04.0297

Baum, M. E., Licht, M. A., Huber, I., & Archontoulis, S. V. (2020). Impacts of climate change on the optimum planting date of different maize cultivars in the central US Corn Belt. *European Journal of Agronomy*, *119*, 126101. https://doi.org/10.1016/j.eja.2020.126101

Bausch, W., Trout, T., & Buchleiter, G. (2011). Evapotranspiration adjustments for deficit irrigated corn using canopy temperature: A concept. *Irrigation and Drainage*, *60*, 682–693. https://doi.org/10.1002/ird.601

Bayer Crop Sciences. (2022). *Corn yield potential and row spacing*. https://www.cropscience.bayer.us/articles/dad/corn-row-spacing

Bellasio, C., & Griffiths, H. (2014). Acclimation to low light by C4 maize: Implications for bundle sheath leakiness. *Plant, Cell, and Environment*, *37*, 1046–1058.

Bevacqua, E., Zappa, G., Lehner, F., & Zscheischler, J. (2022). Precipitation trends determine future occurrences of compound hot-dry events. *Nature Climate Change*, *12*, 350–355. https://doi.org/10.1038/s41558-022-01309-5

Bollero, G. A., Bullock, D. G., & Hollinger, S. E. (1996). Soil temperature and planting date effects on corn yield, leaf area, and plant development. *Agronomy Journal*, *88*, 385–390. https://doi.org/10.2134/agronj1996.00021962008800030005x

Bonhomme, R., Derieux, M., & Edmeades, G. O. (1994). Flowering of diverse maize cultivars in relation to temperature and photoperiod in multi-location field trials. *Crop Science*, *34*, 156–164. https://doi.org/10.2135/cropsci1994.0011183x003400010028x

Boomsma, C. R., Santini, J. B., Tollenaar, M., & Vyn, T. J. (2009). Maize morphological responses to intense crowding and low nitrogen availability: An analysis and review. *Agronomy Journal*, *101*, 1426–1452. https://doi.org/10.2134/agronj2009.0082

Bruce, W. B., Edmeades, G. O., & Barker, T. C. (2002). Molecular and physiological approaches to maize improvement for drought tolerance. *Journal of Experimental Botany*, *53*, 13–25. https://doi.org/10.1093/jexbot/53.366.13

Burgess, A. J., & Cardoso, A. A. (2022). Throwing shade: Limitations to photosynthesis at high plant densities and how to overcome them. *Plant Physiology*, *191*, 825–827. https://doi.org/10.1093/plphys/kiac567

Burke, M., Driscoll, A., Heft-Neal, S., Xue, J., Burney, J., & Wara, M. (2021). The changing risk and burden of wildfire in the United States. *Proceedings of the National Academy of Sciences*, *118*(2), e2011048118. https://doi.org/10.1073/pnas.2011048118

Busari, M. A., Kukal, S. S., Kaur, A., Bhatt, R., & Dulazi, A. A. (2015). Conservation tillage impacts on soil, crop and the environment. *International Soil and Water Conservation Research*, *3/2*, 119–129.

Çakir, R. (2004). Effect of water stress at different development stages on vegetative and reproductive growth of corn. *Field Crops Research*, *89*, 1–16. https://doi.org/10.1016/j.fcr.2004.01.005

Campillo, C., Fortes, R., & Prieto, M. d. H. (2012). Solar radiation effect on crop production. In E. B. Babatunde (Ed.), *Solar radiation* (pp. 167–191). IntechOpen. https://doi.org/10.5772/34796

Campos, H., Cooper, M., Edmeades, G. O., Loffler, C., Schussler, J. R., & Ibanez, M. (2006). Changes in drought tolerance in maize associated with fifty years of breeding for yield in the US Corn Belt. *Maydica*, *51*, 369–381. https://inis.iaea.org/search/search.aspx?orig_q=RN

Cantarero, M. G., Cirilo, A. G., & Andrade, F. H. (1999). Night temperature at silking affects set in maize. *Crop Science*, *39*, 703–710. https://doi.org/10.2135/cropsci1999.0011183x003900020017x

Cates, A., & DeJong-Hughes, J. (2022, October 29). Minnesota: Managing residue in a dry year. AgFax. https://www.agfax.com/2022/10/29/minnesota-managing-residue-in-a-dry-year/

Cavanagh, A. P., South, P. F., Bernacchi, C. J., & Ort, D. R. (2022). Alternative pathway to photorespiration protects growth and productivity at elevated temperatures in a model crop. *Plant Biotechnology Journal*, *20*, 711–721. https://doi.org/10.1111/pbi.13750

Céline, C. (2019). Senescence: The genetics behind stay-green corn. *Plant Cell*, *31*, 1934–1935. https://doi.org/10.1105/tpc.19.00465

Chang, J. H. (1981). Corn yield in relation to photoperiod, night temperature, and solar radiation. *Agricultural Meteorology*, *24*(C), 253–262. https://doi.org/10.1016/0002-1571(81)90049-2

Che, H. Z., Shi, G. Y., Zhang, X. Y., Arimoto, R., Zhao, J. Q., Xu, L., Wang, B., & Chen, Z. H. (2005). Analysis of 40 years of solar radiation data from China, 1961–2000. *Geophysical Research Letters*, *32*(6), L06803. https://doi.org/10.1029/2004GL022322

Chen, Q., Zhong, H., Fan, X.-W., & Li, Y.-Z. (2015). An insight into the sensitivity of maize to photoperiod changes under controlled conditions. *Plant, Cell & Environment*, *38*, 1479–1489. https://doi.org/10.1111/pce.12361

Chung, U., Gbegbelegbe, S., Shiferaw, B., Robertson, R., Yun, J. I., Tesfaye, K., Hoogenboom, G., & Sonder, K. (2014). Modeling the effect of a heat wave on maize production in the USA and its implications on food security in the developing world. *Weather and Climate Extremes*, *5–6*, 67–77. https://doi.org/10.1016/j.wace.2014.07.002

Ciampitti, I., Adee, E., Roozeboom, K., Schlegel, A., Cramer, G., Duncan, S., & Shoup, D. (2015). *Drought-tolerant corn hybrids: Yield benefits*. Kansas State University. https://eupdate.agronomy.ksu.edu/article_new/drought-tolerant-corn-hybrids-yield-benefits-501-4

Ciampitti, I. A., & Vyn, T. J. (2011). A comprehensive study of plant density consequences on nitrogen uptake dynamics of maize plants from vegetative to reproductive stages. *Field Crops Research*, *121*, 2–18. https://doi.org/10.1016/j.fcr.2010.10.009

Clarke, J. M., DePauw, R. M., & Townley-Smith, T. F. (1992). Evaluation of methods for quantification of drought tolerance in wheat. *Crop Science*, *32*, 723–728. https://doi.org/10.2135/cropsci1992.0011183x003200030029x

Clevenger, B. (2020). *Now is the time to adjust your water table level*. Crop Observation and Recommendation Network Newsletter. Ohio State University Extension. https://agcrops.osu.edu/newsletter/corn-newsletter/2020-39/now-time-adjust-your-water-table-level

Cook, B. I., Ault, T. R., & Smerdon, J. E. (2015). Unprecedented 21st century drought risk in the American Southwest and Central Plains. *Science Advances*, *1*, e1400082. https://doi.org/10.1126/sciadv.1400082

Cooper, M., Gho, C., Leafgren, R., Tang, T., & Messina, C. (2014). Breeding drought-tolerant maize hybrids for the U.S. corn-belt: Discovery to product. *Journal of Experimental Botany*, *65*, 6191–6204. https://doi.org/10.1093/jxb/eru064

Crookston, B. S., Yost, M. A., Bowman, M., Veum, K., Cardon, G., & Norton, J. (2021). Soil health spatial-temporal variation influence soil security on Midwestern, U.S. farms. *Soil Security*, *3*, 100005. https://doi.org/10.1016/j.soisec.2021.100005

Dai, A. (2013). Increasing drought under global warming in observations and models. *Nature Climate Change*, *3*, 52–58. https://doi.org/10.1038/nclimate1633

Daryanto, S., Wang, L., & Jacinthe, P. A. (2016). Global synthesis of drought effects on maize and wheat production. *PLoS One*, *11*, e0156362. https://doi.org/10.1371/journal.pone.0156362

DeFelice, M. S., Carter, P. R., & Mitchell, S. B. (2006). Influence of tillage on corn and soybean yield in the United States and Canada. *Crop Management*, *5/1*, 1–7. https://doi.org/10.1094/CM-2006-0626-01-RS

DeLucia, E. H., Chen, S., Guan, K., Peng, B., Li, Y., Gomez-Casanovas, N., Kantola, I. B., Bernacchi, C. J., Huang, Y., Long, S. P., & Ort, D. R. (2019). Are we approaching a water ceiling to maize yields in the United States? *Ecosphere*, *10*, e02773. https://doi.org/10.1002/ecs2.2773

Dietzel, R., Liebman, M., Ewing, R., Helmers, M., Horton, R., Jarchow, M., & Archontoulis, S. (2016). How efficiently do corn-and soybean-based cropping systems use water? A systems modeling analysis. *Global Change Biology*, *22*, 666–681. https://doi.org/10.1111/gcb.13101

Djaman, K., & Irmak, S. (2012). Soil water extraction patterns and crop, irrigation, and evapotranspiration water use efficiency of maize under full and limited irrigation and rainfed settings. *Transactions of the American Society of Agricultural Engineers*, *55*, 1223–1238. https://doi.org/10.13031/2013.42262

Djaman, K., Owen, C., West, M. M., Allen, S., Koudahe, K., Darapuneni, M., & O'Neill, M. (2020). Relationship between relative maturity and grain yield of maize (*Zea mays* L.) hybrids in Northwest New Mexico for the 2003–2019 period. *Agriculture*, *10*, 290. https://doi.org/10.3390/agriculture10070290

Duiker, S. W. (2022). *Strategies to decrease drought risk in crop production*. Penn State University Extension. State College, PA. https://extension.psu.edu/strategies-to-decrease-drought-risk-in-crop-production

Durand, M., Murchie, E. H., Lindfors, A. V., Urban, O., Aphalo, P. J., & Robson, T. M. (2021). Diffuse solar radiation and canopy photosynthesis in a changing environment. *Agricultural and Forest Meteorology*, *311*, 108684. https://doi.org/10.1016/j.agrformet.2021.108684

Earley, E. B., Miller, R. J., Reichert, G. L., Hageman, R. H., & Seif, R. D. (1966). Effect of shade on maize production under field conditions. *Crop Science*, *6*(1), 1–7. https://doi.org/10.2135/cropsci1966.0011183x000600010001x

Eastman, R., & Warren, S. G. (2013). A 39-yr survey of cloud changes from land stations worldwide 1971–2009: Long-term trends, relation to aerosols, and expansion of the tropical belt. *Journal of Climate*, *26*(4), 1286–1303. https://doi.org/10.1175/JCLI-D-12-00280.1

Edwards, G. E., & Walker, D. A. (1983). *C_3, C_4: Mechanism and cellular and environmental regulation of photosynthesis*. Blackwell Scientific Publications.

Ehleringer, J. R., Cerling, T. E., & Helliker, B. R. (1997). C_4 photosynthesis, atmospheric CO_2, and climate. *Oecologia*, *112*(3), 285–299. https://doi.org/10.1007/s004420050311

Elmore, R., Yang, H., & Hoegemeyer, T. (2019). *Corn and clouds: "…from both sides now…"* University of Nebraska Extension CropWatch.

Falkenmark, M. (2013). Growing water scarcity in agriculture: Future challenge to global water security. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *371*, 20120410. https://doi.org/10.1098/rsta.2012.0410

Finlay, K. W., & Wilkinson, G. N. (1963). The analysis of adaptation in a plant breeding programme. *Australian Journal of Agricultural Research Society*, *14*, 742–754. https://doi.org/10.1071/AR9630742

Fortin, M.-C., Pierce, F. J., & Edwards, M. (1994). Corn leaf area response to early-season soil temperature under crop residues. *Agronomy Journal*, *86*, 355–359.

Fu, Y., Li, X., Zhou, X., Geng, X., Guo, Y., & Zhang, Y. (2020). Progress in plant phenology modeling under global climate change. *Science China Earth Sciences*, *63*, 1237–1247. https://doi.org/10.1007/s11430-019-9622-2

Gao, J., Zhao, B., Dong, S., Liu, P., Ren, B., & Zhang, J. (2017). Response of summer maize photosynthate accumulation and distribution to shading stress assessed by using $^{13}CO_2$ stable isotope tracer in the field. *Frontiers in Plant Science*, *8*, 1821. https://www.frontiersin.org/articles/10.3389/fpls.2017.01821

Gewin, V. (2022). *A wild, windy spring is creating a soil erosion nightmare for farmers*. https://civileats.com/2022/06/06/a-wild-windy-spring-is-creating-a-soil-erosion-nightmare-for-farmers/amp/

Gilmore, E. C., & Rogers, J. S. (1958). Heat units as a method of measuring maturity in corn. *Agronomy Journal*, *50*, 611–615. https://doi.org/10.2134/agronj1958.00021962005000100014x

GLISA. (2017). *Climate change in the Great Lakes region*. http://glisa.umich.edu/gl-climate-factsheet-refs

Graham, E. R., Lopez, L., & Dean, T. M. (1972). Artificial light as a factor influencing yields of high-population corn. *Transactions of the ASAE*, *15*, 576–579.

Grassini, P., Yang, H., & Cassman, K. G. (2009). Limits to maize productivity in Western Corn-Belt: A simulation analysis for fully irrigated and rainfed conditions. *Agricultural and Forest Meteorology*, *149*, 1254–1265. https://doi.org/10.1016/j.agrformet.2009.02.012

Guo, X., Yang, Y., Liu, H., Liu, G., Liu, W., Wang, Y., Zhao, R., Ming, B., Xie, R., Wang, K., Li, S., & Hou, P. (2022). Effects of Solar radiation on dry matter distribution and root morphology of high yielding maize cultivars. *Agriculture*, *12*(2), 299. https://doi.org/10.3390/agriculture12020299

Hao, B., Xue, Q., Marek, T. H., Jessup, K. E., Becker, J., Hou, X., Xu, W., Bynum, E. D., Bean, B. W., & Colaizzi, P. D. (2015). Water use and grain yield in drought-tolerant corn in the Texas High Plains. *Agronomy Journal*, *107*, 1922–1930. https://doi.org/10.2134/agronj15.0133

Hardacre, A. K., & Turnbull, H. L. (1986). The growth and development of maize (*Zea mays* L.) at five temperatures. *Annals of Botany*, *58*, 779–787. https://doi.org/10.1093/oxfordjournals.aob.a087260

Hashemi-Dezfouli, A., & Herbert, S. J. (1992). Intensifying plant density response of corn with artificial shade. *Agronomy Journal*, *84*(4), 547–551. https://doi.org/10.2134/agronj1992.00021962008400040001x

Hatfield, J. L., & Dold, C. (2018). Climate change impacts on corn phenology and productivity. In Dr. Amanullah & S. Fahad (Eds.), *Corn—Production and human health in changing climate* (pp. 95–114) IntechOpen. https://doi.org/10.5772/intechopen.76933

Hatlitligil, M., Olson, R., & Compton, W. (1984). Yield, water use, and nutrient uptake of corn hybrids under varied irrigation and nitrogen regimes. *Fertilizer Research*, *5*, 321–333. https://doi.org/10.1007/BF01051632

Hauser, C., & Jimenez, J. (2022, May 13). *Haboob? Derecho? By any name, plains dust storm was strong*. The New York Times. https://www.nytimes.com/2022/05/13/us/haboob-dust-storm-upper-plains.html

Hemes, K. S., Verfaillie, J., & Baldocchi, D. D. (2020). Wildfire-smoke aerosols lead to increased light use efficiency among agricultural and restored wetland land uses in California's Central Valley. *Journal of Geophysical Research: Biogeosciences*, *125*(2), e2019JG005380. https://doi.org/10.1029/2019JG005380

Henderson, S., & Perry, R. (1966). *Agricultural process engineering*. AVI Publishing Company.

Imholte, A. A., & Carter, P. R. (1987). Planting date and tillage effects on corn following corn. *Agronomy Journal*, *79*, 746–751. https://doi.org/10.2134/agronj1987.00021962007900040032x

Jeschke, M. (2021a). *Crop insights: Heat stress effects on corn*. Pioneer Agronomy Sciences. https://corteva.showpad.com/share/XvSbu1v7dHZJaDljL6gHl

Jeschke, M. (2021b). *Is smoke from wildfires affecting crop yields?* Pioneer Agronomy. https://www.pioneer.com/us/agronomy/wildfires-crop-yields.html

Jong, S. K., Brewbaker, J. L., & Lee, C. H. (1982). Effects of solar radiation on the performance of maize in 41 successive monthly plantings in Hawaii. *Crop Science*, *22*(1), 13–18. https://doi.org/10.2135/cropsci1982.0011183X002200010004x

Juliano, T. W., Jiménez, P. A., Kosović, B., Eidhammer, T., Thompson, G., Berg, L. K., Fast, J., Motley, A., & Polidori, A. (2022). Smoke from 2020 United States wildfires responsible for substantial solar energy forecast errors. *Environmental Research Letters*, *17*(3), 034010. https://doi.org/10.1088/1748-9326/ac5143

Kansas Department of Agriculture. (2013). *Kansas farm facts*. https://agriculture.ks.gov/docs/default-source/documents-office-of-the-secretary/kansas-farm-facts-august-2013.pdf?sfvrsn=5

Kim, K. I., Clay, D. E., Carlson, C. G., Clay, S. A., & Trooien, T. (2008). Do synergistic relationships between nitrogen and water influence the ability of corn to use nitrogen derived from fertilizer and soil? *Agronomy Journal*, *100*, 551–556. https://doi.org/10.2134/agronj2007.0064

Kim, Y., Kimball, J. S., Zhang, K., & McDonald, K. C. (2012). Satellite detection of increasing Northern Hemisphere non-frozen seasons from 1979 to 2008: Implications for regional vegetation growth. *Remote Sensing of Environment*, *121*, 472–487. https://doi.org/10.1016/j.rse.2012.02.014

Kiniry, J. R., & Ritchie, J. T. (1985). Shade-sensitive interval of kernel number of maize. *Agronomy Journal*, *77*(5), 711–715. https://doi.org/10.2134/agronj1985.00021962007700050012x

Knapp, A. K., & Fay, P. A. (1997). Plant strategies for coping with variable light regimes. In A. S. Basra & R. K. Basra (Eds.), *Mechanisms of environmental stress resistance in plants* (pp. 191–212). Routledge.

Kranz, W. L., Irmak, S., Van Donk, S. J., Yonts, C. D., & Mar-tin, D. L. (2008). *Irrigation management for corn. Nebguide G1850*. University of Nebraska-Lincoln. http://extensionpublications.unl.edu/assets/html/g1850/build/g1850.htm

Kratochvil, R. J., Harrison Jr, M., & Pearce, J. T. (2005). Evaluation of double crop corn production. *Mid-Atlantic Grain Forage Journal*, *9*, 18–29.

Krupek, F. S., Mizero, S. M., Redfearn, D., & Basche, A. (2022). Assessing how cover crops close the soil health gap in on-farm experiments. *Agricultural & Environmental Letters*, *7*, e20088. https://doi.org/10.1002/ael2.20088

Kumudini, S., Andrade, F. H., Boote, K. J., Brown, G. A., Dzotsi, K. A., Edmeades, G. O., Gocken, T., Goodwin, M., Halter, A. L., Hammer, G. L., Hatfields, J. L., Jones, J. W., Kemanian, A. R., Kim, S.-H., Kiniry, J., Lizaso, J. I., Nendel, C., Nielsen, R. L., … Tollenaar, M. (2014). Predicting maize phenology: Intercomparison of functions for developmental response to temperature. *Agronomy Journal*, *106*, 2087–2097. https://doi.org/10.2134/agronj14.0200

Lacasa, J., Ciampitti, I. A., Amas, J. I., Curin, F., Luque, S. F., & Otegui, M. E. (2022). Breeding effects on canopy light attenuation in maize: A retrospective and prospective analysis. *Journal of Experimental Botany*, *73*, 1301–1311. https://doi.org/10.1093/jxb/erab503

Lauer, J. G., Carter, P. R., Wood, T. M., Diezel, G., Wiersma, D. W., Rand, R. E., & Mlynarek, M. J. (1999). Corn hybrid response to planting date in the northern Corn Belt. *Agronomy Journal*, *91*, 834–839. https://doi.org/10.2134/agronj1999.915834x

Levitt, J. (1972). Drought tolerance. In J. Levitt (Ed.), *Responses of plants to environmental stresses* (pp. 379–424). Academic Press.

Li, Y., Guan, K., Peng, B., Franz, T. E., Wardlow, B., & Pan, M. (2020). Quantifying irrigation cooling benefits to maize yield in the US Midwest. *Global Change Biology*, *26*, 3065–3078. https://doi.org/10.1111/gcb.15002

Li, Y.-T., Luo, J., Liu, P., & Zhang, Z.-S. (2021). C_4 species utilize fluctuating light less efficiently than C_3 species. *Plant Physiology*, *187*, 1288–1291. https://doi.org/10.1093/plphys/kiab411

Licht, M. A., Parvej, M. R., & Wright, E. E. (2019). Corn yield response to row spacing and plant population in Iowa. *Crop, Forage & Turfgrass Management*, *5*, 1–7. https://doi.org/10.2134/cftm2019.05.0032

Liepert, B. G. (2002). Observed reductions of surface solar radiation at sites in the United States and worldwide from 1961 to 1990: Observed reductions of surface solar radiation. *Geophysical Research Letters*, *29*(10), 61–64. https://doi.org/10.1029/2002GL014910

Lindquist, J. L., Arkebauer, T. J., Walters, D. T., Cassman, K. G., & Dobermann, A. (2005). Maize radiation use efficiency under optimal growth conditions. *Agronomy Journal*, *97*, 72–78. https://doi.org/10.2134/agronj2005.0072

Lindsey, A. (2020). *Extended drydown in corn*. https://agcrops.osu.edu/newsletter/corn-newsletter/2020-36/extended-drydown-corn

Lindsey, A., Lindsey, L., & Ortez, O. (2023). *How could the haze of wildfires affect crop growth?* C.O.R.N. Newsletter. Ohio State University Extension. https://agcrops.osu.edu/newsletter/corn-newsletter/2023-21/how-could-haze-wildfires-affect-crop-growth

Lindsey, A., Lindsey, L., & Wilson, A. (2021). *Hazy days…How does light influence corn and soybean?* C.O.R.N. Newsletter. Ohio State University Extension. https://agcrops.osu.edu/newsletter/corn-newsletter/2021-26/hazy-days%E2%80%A6how-does-light-influence-corn-and-soybean

Lindsey, A. J., Barker, D. J., Metzger, J. D., Mullen, R. W., & Thomison, P. R. (2018). Physiological and morphological response of a drought-tolerant maize hybrid to agronomic management. *Agronomy Journal*, *110*(4), 1354–1362. https://doi.org/10.2134/agronj2018.01.0034

Lindsey, A. J., Minyo, R., Geyer, A., & Thomison, P. R. (2020). Comparing the agronomic performance of short-season and commonly grown hybrid maturities in Ohio. *Crop, Forage & Turfgrass Management*, *6*, e20019. https://doi.org/10.1002/cft2.20019

Lindsey, A. J., & Thomison, P. R. (2016). Drought-tolerant corn hybrid and relative maturity yield response to plant population and planting date. *Agronomy Journal*, *108*(1), 229–242. https://doi.org/10.2134/agronj2015.0200

Lindsey, A. J., Thomison, P. R., Barker, D. J., & Metzger, J. D. (2017). Evaluating water exclusion using plastic ground cover in maize at two population densities. *Agronomy Journal*, *109*, 532–540. https://doi.org/10.2134/agronj2016.09.0508

Lindsey, A. J., Thomison, P. R., Barker, D. J., & Mullen, R. W. (2015). Drought-tolerant corn hybrid response to nitrogen application rate in Ohio. *Crop, Forage and Turfgrass Management*, *1*(1), 1–8. https://doi.org/10.2134/cftm2015.0168

Lindsey, L. E., Richer, E., McGlinch, G. J., & Lindsey, A. J. (2023). Partial return calculator to compare monocrop, relay-intercrop, and double crop production systems. *Crop, Forage & Turfgrass Management*, *9*, e20208. https://doi.org/10.1002/cft2.20208

Liu, G., Liu, W., Hou, P., Ming, B., Yang, Y., Guo, X., Xie, R., Wang, K., & Li, S. (2021). Reducing maize yield gap by matching plant density and solar radiation. *Journal of Integrative Agriculture*, *20*(2), 363–370. https://doi.org/10.1016/S2095-3119(20)63363-9

Liu, W., & Tollenaar, M. (2009). Physiological mechanisms underlying heterosis for shade tolerance in maize. *Crop Science*, *49*(5), 1817–1826. https://doi.org/10.2135/cropsci2008.07.0423

Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science*, *319*, 607–610. https://doi.org/10.1126/science.1152339

Lobell, D. B., & Field, C. B. (2007). Global scale climate–crop yield relationships and the impacts of recent warming. *Environmental Research Letters*, *2*, 1–7. https://doi.org/10.1088/1748-9326/2/1/014002

Long, N. V., Assefa, Y., Schwalbert, R., & Ciampitti, I. A. (2017). Maize yield and planting date relationship: A synthesis-analysis for US high-yielding contest-winner and vield research data. *Frontiers in Plant Science*, *8*, 2106. https://doi.org/10.3389/fpls.2017.02106

Loomis, R. S., & Connor, D. J. (1992). Photosynthesis. *Crop ecology—Productivity and management in agricultural systems* (pp. 257–288. Cambridge University Press. https://doi.org/10.1017/CBO9781139170161.014

Loomis, R. S., & Williams, W. A. (1963). Maximum crop productivity: An extimate. *Crop Science*, *3*(1), 67–72. https://doi.org/10.2135/cropsci1963.0011183x000300010021x

Lopes, M. S., Araus, J. L., Van Heerden, P. D., & Foyer, C. H. (2011). Enhancing drought tolerance in C_4 crops. *Journal of Experimental Botany*, *62*, 3135–3153. https://doi.org/10.1093/jxb/err105

Manley, J., van Kooten, G. C., Moeltner, K., & Johnson, D. W. (2005). Creating carbon offsets in agriculture through no-till cultivation: A meta-analysis of costs and carbon benefits. *Climatic Change*, *68*, (1–2), 41–65.

Martinez-Feria, R. A., Licht, M. A., Ordóñez, R. A., Hatfield, J. L., & Coulter, J. A. (2019). Evaluating maize and soybean grain dry-down in the field with predictive algorithms and genotype-by-environment analysis. *Scientific Reports*, *9*, 7167. https://doi.org/10.1038/s41598-019-43653-1

Mbewe, D. M. N., & Hunter, R. B. (1986). The effect of shade stress on the performance of corn for silage versus grain. *Canadian Journal of Plant Science*, *66*(1), 53–60. https://doi.org/10.4141/cjps86-007

McGrath, J. M., Betzelberger, A. M., Wang, S., Shook, E., Zhu, X.-G., Long, S. P., & Ainsworth, E. A. (2015). An analysis of ozone damage to historical maize and soybean yields in the United States. *Proceedings of the National Academy of Sciences*, *112*(46), 14390–14395. https://doi.org/10.1073/pnas.1509777112

Messina, C., Ciampitti, I. A., Berning, D., Bubeck, D., Hammer, G., & Cooper, M. (2022). Sustained improvement in tolerance to water deficit accompanies maize yield increase in temperate environments. *Crop Science*, *62*, 2138–2150. https://doi.org/10.1002/csc2.20781

Messina, C., McDonald, D., Poffenbarger, H., Clark, R., Salinas, A., Fang, Y., Gho, C., Tang, T., Graham, G., Hammer, G. L., & Cooper, M. (2021). Reproductive resilience but not root architecture underpins yield improvement under drought in maize. *Journal of Experimental Botany*, *72*, 5235–5245. https://doi.org/10.1093/jxb/erab231

Messina, C., Rotundo, J., Hammer, G. L., Gho, C., Reyes, A., Fang, Y., van Oosterom, E., Borras, L., & Cooper, M. (2022). Radiation use efficiency increased over a century of maize (*Zea mays* L.) breeding in the US corn belt. *Journal of Experimental Botany*, *73*, 5503–5513. https://doi.org/10.1093/jxb/erac212

Mohammed, Y. A., Gesch, R. W., Wells, S. S., Heller, N. J., Lindsey, A. J., Hard, A. W., Phippen, W. B., & Bedeker, B. (2023). Yield tradeoffs of early corn harvest to enhance pennycress establishment. *Agronomy Journal*, *115*, 1762–1775. https://doi.org/10.1002/agj2.21370

Moss, D. N., & Musgrave, R. B. (1971). Photosynthesis and crop production. In N. C. Brady (Ed.), *Advances in agronomy* (Vol. 23, pp. 317–336). Academic Press. https://doi.org/10.1016/S0065-2113(08)60155-8

Muchow, R. C., Sinclair, T. R., & Bennett, J. M. (1990). Temperature and solar radiation effects on potential maize yield across locations. *Agronomy Journal*, *82*(2), 338–343. https://doi.org/10.2134/agronj1990.00021962008200020033x

National Drought Mitigation Center. (2022). *U.S. drought monitor map archive*. University of Nebraska. http://droughtmonitor.unl.edu/Maps/MapArchive.aspx

National Interagency Fire Center. (2021). *National Interagency Fire Center Wildfire Statistics*. https://www.nifc.gov/fire-information/statistics

National Solar Radiation Database. (2023). *National Renewable Energy Laboratory*. https://nsrdb.nrel.gov/data-viewer

Nemali, K. S., Bonin, C., Dohleman, F. G., Stephens, M., Reeves, W. R., Nelson, D. E., Castiglioni, P., Whitsel, J. E., Sammons, B., Silady, R. A., Anstrom, D., Sharp, R. E., Patharkar, O. R., Clay, D., Coffin, M., Nemeth, M. A., Leibman, M. E., Luethy, M., & Lawson, M. (2015). Physiological responses related to increased grain yield under drought in the first biotechnology-derived drought-tolerant maize. *Plant, Cell & Environment*, *38*, 1866–1880. https://doi.org/10.1111/pce.12446

Nemergut, K. T., Thomison, P. R., Carter, P. R., & Lindsey, A. J. (2021). Planting depth affects corn emergence, growth and development, and yield. *Agronomy Journal*, *113*, 3351–3360. https://doi.org/10.1002/agj2.20701

Nielsen, R. L. (1988). Influence of hybrids and plant density on grain yield and stalk breakage in corn grown in 15-inch row spacing. *Journal of Production Agriculture*, *1*(3), 190–195. https://doi.org/10.2134/jpa1988.0190

Nielsen, R. L. (2012). *Interpreting corn hybrid maturity ratings*. https://www.agry.purdue.edu/ext/corn/news/timeless/HybridMaturity.html

Nielsen, R. L. (2019). *Late planted corn not maturing as expected*. https://www.agry.purdue.edu/ext/corn/news/articles_19/LatePlantedCornMaturity_1012.html

Nielsen, R. L., Thomison, P. R., Brown, G. A., Halter, A. L., Wells, J., & Wuethrich, K. L. (2002). Delayed planting effects on flowering and grain maturation of dent corn. *Agronomy Journal*, *94*, 549–558.

Ogola, J. B. O., Wheeler, T. R., & Harris, P. M. (2002). Effects of nitrogen and irrigation on water use of maize crops. *Field Crops Research*, *78*, 105–117. https://doi.org/10.1016/S0378-4290(02)00116-8

O'Neill, P. M., Shanahan, J. F., Schepers, J. S., & Caldwell, B. (2004). Agronomic responses of corn hybrids from different eras to deficit and adequate levels of water and nitrogen. *Agronomy Journal*, *96*, 1660–1667. https://doi.org/10.2134/agronj2004.1660

Orner, B. (2021). *Central Ohio is seeing more smoky days from western wildfires, threatening health and crops*. https://www.nbc4i.com/weather/climate-columbus/central-ohio-is-seeing-more-smoky-days-from-western-wildfires-threatening-health-and-crops/

Ortez, O., Lindsey, A., & LaBarge, G. (2022). *Crop water use in corn—What do we know?* Ohio State University Extension, Electronic Newsletter Article. https://agcrops.osu.edu/newsletter/corn-newsletter/2022-23/crop-water-use-corn-%E2%80%93-what-do-we-know

Ortez, O. A., McMechan, A. J., Hoegemeyer, T., Ciampitti, I. A., Nielsen, R. L., Thomison, P., Abendroth, L. J., & Elmore, R. W. (2022). Conditions potentially affecting corn ear formation, yield, and abnormal ears: A review. *Crop, Forage & Turfgrass Management*, *8*, e20173. https://doi.org/10.1002/cft2.20173

Otegui, M. E., Andrade, F. H., & Suero, E. E. (1995). Growth, water use, and kernel abortion of maize subjected to drought at silking. *Field Crops Research*, *40*, 87–94. https://doi.org/10.1016/0378-4290(94)00093-R

Ottman, M. J., & Welch, L. F. (1988). Supplemental radiation effects on senescence, plant nutrients, and yield on field-grown corn. *Agronomy Journal*, *80*, 619–626.

Panda, R. K., Behera, S. K., & Kashyap, P. S. (2004). Effective management of irrigation water for maize under stressed conditions. *Agricultural Water Management*, *66*, 181–203. https://doi.org/10.1016/j.agwat.2003.12.001

Parent, B., Leclere, M., Lacube, S., Semenov, M. A., Welcker, C., Martre, P., & Tardieu, F. (2018). Maize yields over Europe may increase in spite of climate change, with an appropriate use of the genetic variability of flowering time. *PNAS*, *115*, 10642–10647. https://doi.org/10.1073/pnas.1720716115

Payero, J. O., Tarkalson, D. D., Irmak, S., Davison, D., & Petersen, J. L. (2009). Effect of timing of a deficit-irrigation allocation on corn evapotranspiration, yield, water use efficiency and dry mass. *Agricultural Water Management*, *96*, 1387–1397. https://doi.org/10.1016/j.agwat.2009.03.022

Peters, D. B., Pendleton, J. W., Hageman, R. H., & Brown, C. M. (1971). Effect of night temperature on grain yield of corn, wheat, and soybeans. *Agronomy Journal*, *63*, 809.

Quin, F. M. (1981). Night respiration of a maize crop in the Lowland Humid Tropics. *Journal of Applied Ecology*, *18*, 497–506. https://doi.org/10.2307/2402411

Quinn, D. J. (2023). *How does wildfire smoke impact corn growth?* Purdue University Pest & Crop Newsletter. https://extension.entm.purdue.edu/newsletters/pestandcrop/article/how-does-wildfire-smoke-impact-corn-growth/

Rattalino-Edreira, J. I., Budakli-Carpici, E., Sammarro, D., & Otegui, M. E. (2011). Heat stress effects around flowering on kernel set of temperate and tropical maize hybrids. *Field Crops Research*, *123*, 62–73. https://doi.org/10.1016/j.fcr.2011.04.015

Rattalino-Edreira, J. I., & Otegui, M. E. (2012). Heat stress in temperate and tropical maize hybrids: Differences in crop growth, biomass partitioning and reserves use. *Field Crops Research*, *130*, 87–98. https://doi.org/10.1016/j.fcr.2012.02.009

Reddy, V. M., & Daynard, T. B. (1983). Endosperm characteristics associated with rate of grain filling and kernel size in corn. *Maydica*, *28*, 339–355.

Reed, A. J., Singletary, G. W., Schussler, J. R., Williamson, D. R., & Christy, A. L. (1988). Shading effects on dry matter and nitrogen partitioning, kernel number, and yield of maize. *Crop Science*, *28*(5), 819–825. https://doi.org/10.2135/cropsci1988.0011183X002800050020x

Reyes, A., Messina, C. D., Hammer, G. L., Liu, L., van Oosterom, E., Lafitte, R., & Cooper, M. (2015). Soil water capture trends over 50 years of single-cross maize (*Zea mays* L.) breeding in the US corn belt. *Journal of Experimental Botany*, *66*, 7339–7346. https://doi.org/10.1093/jxb/erv430

Rizzo, G., Monzon, J. P., Tenorio, F. A., Howard, R., Cassman, K. G., & Grassini, P. (2022). Climate and agronomy, not genetics, underpin recent maize yield gains in favorable environments. *Proceedings of the National Academy of Sciences*, *119*(4), e2113629119. https://doi.org/10.1073/pnas.2113629119

Rochette, P., Desjardins, R. L., Pattey, E., & Lessard, R. (1996). Instantaneous measurement of radiation and water use efficiencies of a maize crop. *Agronomy Journal*, *88*, 627–635. https://doi.org/10.2134/agronj1996.00021962008800040022x

Roth, J. A., Ciampitti, I. A., & Vyn, T. J. (2013). Physiological evaluations of recent drought-tolerant maize hybrids at varying stress levels. *Agronomy Journal*, *105*, 1129–1141. https://doi.org/10.2134/agronj2013.0066

Rudnick, D. R., & Irmak, S. (2013). Impact of water and nitrogen management strategies on maize yield and water productivity indices under linear-move sprinkler irrigation. *Transactions of the ASABE*, *56*, 1769–1783. https://doi.org/10.13031/trans.56.10215

dos Santos, C. L., Abendroth, L. J., Coulter, J. A., Nafziger, E. D., Suyker, A., Yu, J., Schnable, P. S., & Archontoulis, S. V. (2022). Maize leaf appearance rates: A synthesis from the United States Corn Belt. *Frontiers in Plant Science*, *13*, 872738. https://doi.org/10.3389/fpls.2022.872738

dos Santos, C. L., Miguez, F. E., King, K. A., Ruiz, A., Sciarresi, C., Baum, M. E., Danalatos, G. J. N., Stallman, M., Wiley, E., Olmedo Pico, L., Thies, A., Puntel, L. A., Topp, C. N., Trifunovic, S., Eudy, D., Mensah, C., Edwards, J. W., Schnable, P. S., Lamkey, K. R., … Archontoulis, S. V. (2023). Accelerated leaf appearance and flowering in maize after four decades of commercial breeding. *Crop Science*, *63*, 2750–2762. https://doi.org/10.1002/csc2.21044

Schlemmer, M. R., Francis, D. D., Shanahan, J. F., & Schepers, J. S. (2005). Remotely measuring chlorophyll content in corn leaves with differing nitrogen levels and relative water content. *Agronomy Journal*, *97*, 106–112. https://doi.org/10.2134/agronj2005.0106

Scordo, F., Chandra, S., Suenaga, E., Kelson, S. J., Culpepper, J., Scaff, L., Tromboni, F., Caldwell, T. J., Seitz, C., Fiorenza, J. E., Williamson, C. E., Sadro, S., Rose, K. C., & Poulson, S. R. (2021). Smoke from regional wildfires alters lake ecology. *Scientific Reports*, *11*(1), 10922. https://doi.org/10.1038/s41598-021-89926-6

Seifert, C. A., Roberts, M. J., & Lobell, D. B. (2017). Continuous corn and soybean yield penalties across hundreds of thousands of fields. *Agronomy Journal*, *109*, 541–548. https://doi.org/10.2134/agronj2016.03.0134

Sekhon, R. S., Saski, C., Kumar, R., Flinn, B. S., Luo, F., Beissinger, T. M., Ackerman, A. J., Breitzman, M. W., Bridges, W. C., de Leon, N., & Kaeppler, S. M. (2019). Integrated genome-scale analysis identifies novel genes and networks underlying senescence in maize. *Plant Cell*, *31*, 1968–1989. https://doi.org/10.1105/tpc.18.00930

Shrestha, R. K., Richer, E., Clevenger, W. B., Davis, M., & Lindsey, L. E. (2021). Effect of mono-, relay-, and double-crop systems on yield and profitability. *Agronomy Journal*, *113*, 1747–1757. https://doi.org/10.1002/agj2.20598

Sinclair, T. R., Shiraiwa, T., & Hammer, G. L. (1992). Variation in crop radiation-use efficiency with increased diffuse radiation. *Crop Science*, *32*, 1281–1284. https://doi.org/10.2135/cropsci1992.0011183x003200050043x

Singer, J. W., Meek, D. W., Sauer, T. J., Prueger, J. H., & Hatfield, J. L. (2011). Variability of light interception and radiation use efficiency in maize and soybean. *Field Crops Research*, *121*, 147–152.

Snyder, B. (2018). *Rainout shelters*. https://plantscience.psu.edu/research/labs/roots/sites/rock-springs/rainout-shelters

South, P. F., Cavanagh, A. P., Lopez-Calcagno, P. E., Raines, C. A., & Ort, D. R. (2018). Optimizing photorespiration for improved crop productivity. *Journal of Integrative Plant Biology*, *60*, 1217–1230. https://doi.org/10.1111/jipb.12709

Spracklen, D. V., Mickley, L. J., Logan, J. A., Hudman, R. C., Yevich, R., Flannigan, M. D., & Westerling, A. L. (2009). Impacts of climate change from 2000 to 2050 on wildfire activity and carbonaceous aerosol concentrations in the western United States. *Journal of Geophysical Research: Atmospheres*, *114*, D20301. https://doi.org/10.1029/2008JD010966

Stinson, H. T., Jr., & Moss, D. N. (1960). Some effects of shade upon corn hybrids tolerant and intolerant of dense planting. *Agronomy Journal*, *52*(8), 482–484. https://doi.org/10.2134/agronj1960.00021962005200080019x

Stöckle, C. O., & Kemanian, A. R. (2009). Crop radiation capture and use efficiency: A framework for crop growth analysis. *Crop physiology: Applications for genetic improvement and agronomy* (pp. 145–170). Academic Press. https://doi.org/10.1016/B978-0-12-374431-9.00007-4

Swan, J. B., Schneider, E. C., Moncrief, J. F., Paulson, W. H., & Peterson, A. E. (1987). Estimating corn growth, yield, and grain moisture from air growing degree days and residue cover. *Agronomy Journal*, *79*(1), 53–60. https://doi.org/10.2134/agronj1987.00021962007900010012x

Tollenaar, M., & Bruulsema, T. W. (1988). Efficiency of maize dry matter production during periods of complete leaf area expansion. *Agronomy Journal*, *80*(4), 580–585. https://doi.org/10.2134/agronj1988.00021962008000040008x

Tollenaar, M., Fridgen, J., Tyagi, P., Stackhouse, Jr., P. W., & Kumudini, S. (2017). The contribution of solar brightening to the US maize yield trend. *Nature Climate Change*, *7*, 275–278. https://doi.org/10.1038/nclimate3234

Tollenaar, M., & Lee, E. A. (2002). Yield potential, yield stability and stress tolerance in maize. *Field Crops Research*, *75*, 161–169. https://doi.org/10.1016/S0378-4290(02)00024-2

Tsimba, R., Edmeades, G. O., Millner, J. P., & Kemp, P. D. (2013a). The effect of planting date on maize grain yields and yield components. *Field Crops Research*, *150*, 135–144.

Tsimba, R., Edmeades, G. O., Millner, J. P., & Kemp, P. D. (2013b). The effect of planting date on maize: Phenology, thermal time durations and growth rates in a cool temperate climate. *Field Crops Research*, *150*, 145–155.

Ul-Allah, S., Ijaz, M., Nawaz, A., Sattar, A., Sher, A., Naeem, M., Shahzad, U., Farooq, U., Nawaz, F., & Mahmood, K. (2020). Potassium application improves grain yield and alleviates drought susceptibility in diverse maize hybrids. *Plants*, *9*, 75. https://doi.org/10.3390/plants9010075

USDA-NASS. (2013). *Crop production: 2012 Summary*. https://downloads.usda.library.cornell.edu/usda-esmis/files/k3569432s/8s45qb85z/12579v877/CropProdSu-01-11-2013.pdf

USDA-NASS. (2022). *United States: Corn production*. https://ipad.fas.usda.gov/rssiws/al/us_cropprod.aspx

Usuda, H., Ku, M. S. B., & Edwards, G. E. (1985). Influence of light intensity during growth on photosynthesis and activity of several key photosynthetic enzymes in a C4 plant (*Zea mays*). *Physiologia Plantarum*, *63*, 65–70.

Van Roekel, R. J., & Coulter, J. A. (2011). Agronomic responses of corn to planting date and planting density. *Agronomy Journal*, *103*, 1414–1422. https://doi.org/10.2134/agronj2011.0071

Veenstra, R. L., Messina, C. D., Berning, D., Haag, L. A., Carter, P., Hefley, T. J., Prasad, P. V. V., & Ciampitti, I. A. (2021). Effect of tillers on corn yield: Exploring trait plasticity potential in unpredictable environments. *Agronomy Journal*, *61*, 3660–3674. https://doi.org/10.1002/csc2.20576

Wang, J., van den Heever, S. C., & Reid, J. S. (2009). A conceptual model for the link between Central American biomass burning aerosols and severe weather over the south central United States. *Environmental Research Letters*, *4*(1), 015003. https://doi.org/10.1088/1748-9326/4/1/015003

Wang, N., Wang, E., Wang, J., Zhang, J., Zheng, B., Huang, Y., & Tan, M. (2018). Modelling maize phenology, biomass growth and yield under contrasting temperature conditions. *Agricultural and Forest Meteorology*, *250–251*, 319–329. https://doi.org/10.1016/j.agrformet.2018.01.005

Wang, X., Guo, Y., Wang, X., Ma, Y., & Li, B. (2008). Estimating photosynthetically active radiation distribution in maize canopies by a three-dimensional incident radiation model. *Functional Plant Biology*, *35*, 867–875.

Wareing, P. F., Khalifa, M. M., & Treharne, K. J. (1968). Rate-limiting processes in photosynthesis at saturating light intensities. *Nature*, *220*, 453–457.

Warrick, R. A. (1980). Drought in the Great Plains: A case study of research on climate and society in the USA. In J. Ausubel & A. K. Biswas (Eds.), *Climatic constraints and human activities* (Vol. 10, pp. 93–123). IIASA proceedings series. Pergamon Press.

Watson, D. J. (1958). The dependence of net assimilation rate on leaf-area index. *Annals of Botany*, *22*(1), 37–54. https://doi.org/10.1093/oxfordjournals.aob.a083596

White, R. H., Anderson, S., Booth, J. F., Braich, G., Draeger, C., Fei, C., Harley, C. D. G., Henderson, S. B., Jakob, M., Lau, C., Admasu, L. M., Narinesingh, V., Rodell, C., Roocroft, E., Weinbarger, K. R., & West, G. (2023). The unprecedented Pacific Northwest heatwave of June 2021. *Nature Communications*, *14*, 727.

Widdicombe, W. D., & Thelen, K. D. (2002). Row width and plant density effects on corn grain production in the northern corn belt. *Agronomy Journal*, *94*, 1020–1023. https://doi.org/10.2134/agronj2002.1020

Wu, H.-Y., Qiao, M.-Y., Zhang, Y.-J., Kang, W. J., Ma, Q.-H., Gao, H.-Y., Zhang, W. F., & Jiang, C. D. (2022). Photosynthetic mechanism of maize yield under fluctuating light environments in the field. *Plant Physiology*, *191*, 957–973. https://doi.org/10.1093/plphys/kiac542

Wubbles, D. J., & Hayhoe, K. (2004). Climate change projections for the United States Midwest. *Mitigation and Adaptation Strategies for Global Climate Change*, *9*, 335–363.

Yang, X. M., Reynolds, W. D., Drury, C. F., & Reeb, M. D. (2021a). Cover crop effects on soil temperature in a clay loam soil in southwestern Ontario. *Canadian Journal of Soil Science*, *101*(4), 761–770. https://doi.org/10.1139/cjss-2021-0070

Yang, Y., Guo, X., Hou, P., Xue, J., Liu, G., Liu, W., Wang, Y., Zhao, R., Ming, B., Xie, R., Wang, K., & Li, S. (2020). Quantitative effects of solar radiation on maize lodging resistance mechanical properties. *Field Crops Research*, *255*, 107906. https://doi.org/10.1016/j.fcr.2020.107906

Yang, Y., Guo, X., Liu, H., Liu, G., Liu, W., Ming, B., Xie, R., Wang, K., Hou, P., & Li, S. (2021b). The effect of solar radiation change on the maize yield gap from the perspectives of dry matter accumulation and distribution. *Journal of Integrative Agriculture*, *20*(2), 482–493. https://doi.org/10.1016/S2095-3119(20)63581-X

Yang, Y., Xu, W., Hou, P., Liu, G., Liu, W., Wang, Y., Zhao, R., Ming, B., Xie, R., Wang, K., & Li, S. (2019). Improving maize grain yield by matching maize growth and solar radiation. *Scientific Reports*, *9*(1), 3635. https://doi.org/10.1038/s41598-019-40081-z

Yue, X., & Unger, N. (2018). Fire air pollution reduces global terrestrial productivity. *Nature Communications*, *9*(1), 3635. https://doi.org/10.1038/s41467-018-07921-4

Zhan, A., Schneider, H., & Lynch, J. P. (2015). Reduced lateral root branching density improves drought tolerance in maize. *Plant Physiology*, *168*, 1603–1615. https://doi.org/10.1104/pp.15.00187

Zhang, N., Qu, Y., Song, Z., Chen, Y., & Jiang, J. (2022). Responses and sensitivities of maize phenology to climate change from 1971 to 2020 in Henan Province, China. *PLoS One*, *17*, e0262289. https://doi.org/10.1371/journal.pone.0262289

How to cite this article: Ortez, O. A., Lindsey, A. J., Thomison, P. R., Coulter, J. A, Singh, M. P., Carrijo, D. R., Quinn, D. J., Licht, M. A., & Bastos, L. (2023). Corn response to long-term seasonal weather stressors: A review. *Crop Science*, 1–26. https://doi.org/10.1002/csc2.21101