Lengthening of maize maturity time is not a widespread climate change adaptation strategy in the US Midwest

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Abstract

Increasing temperatures in the US Midwest are projected to reduce maize yields because warmer temperatures hasten reproductive development and, as a result, shorten the grain fill period. However, there is widespread expectation that farmers will mitigate projected yield losses by planting longer season hybrids that lengthen the grain fill period. Here, we ask: (a) how current hybrid maturity length relates to thermal availability of the local climate, and (b) if farmers are shifting to longer season hybrids in response to a warming climate. To address these questions, we used county-level Pioneer brand hybrid sales (Corteva Agriscience) across 17 years and 650 counties in 10 Midwest states (IA, IL, IN, MI, MN, MO, ND, OH, SD, and WI). Northern counties were shown to select hybrid maturities with growing degree day (GDD°C) requirements more closely related to the environmentally available GDD compared to central and southern counties. This measure, termed “thermal overlap,” ranged from complete 106% in northern counties to a mere 63% in southern counties. The relationship between thermal overlap and latitude was fit using split-line regression and a breakpoint of 42.8°N was identified. Over the 17-years, hybrid maturities shortened across the majority of the Midwest with only a minority of counties lengthening in select northern and southern areas. The annual change in maturity ranged from −5.4 to 4.1 GDD year⁻¹ with a median of −0.9 GDD year⁻¹. The shortening of hybrid maturity contrasts with widespread expectations of hybrid maturity aligning with magnitude of warming. Factors other than thermal availability appear to more strongly impact farmer decision-making such as the benefit of shorter maturity hybrids on grain drying costs, direct delivery to ethanol biorefineries, field operability, labor constraints, and crop genetics availability. Prediction of hybrid choice under future climate scenarios must include climatic factors, physiological-genetic attributes, socio-economic, and operational constraints.

KEYWORDS
climate adaptation, grain fill period, hybrid maturity, maize, Midwest
INTRODUCTION

Future maize (*Zea mays* L.) yields are dependent on plant breeders maintaining genetic gain by developing genotypes adapted to new climatic conditions and farmers optimizing production practices for the expression of the genetic potential (Butler et al., 2018; Grassini et al., 2013). Yield gains over the past four decades have been attributed to breeding for increased stress tolerance and subsequent ability to increase plant density (Duvick, 2005; Lee & Tollenaar, 2007), favorable temperatures and moisture conditions, and advantageous timing of improved farm operations (Butler et al., 2018). As a result, maize yields have improved across environments from well-watered to those with nitrogen and water deficits (Cooper et al., 2014, 2020; Mueller et al. 2019). The yield potential realized from these genetic and management advancements have been enhanced by 5%-10% owing to favorable changes in climate (Partridge et al., 2019).

For the lower latitudes of the Midwest, a lack of warming during the summer has caused the region to be termed a "warming hole" in the climatological literature as it has experienced less warming than expected compared to other intercontinental regions (Intergovernmental Panel on Climate Change, 2014; Pan et al., 2014; Terando et al., 2012). Of particular interest for maize production are changes in temperature during the frost-free period with greater warming at higher latitudes (Alfaro et al., 2006; Mueller et al., 2016; Portmann et al., 2009). Although the total amount of thermal time (a measure relating temperature to crop phenology and development) during the frost-free period is greater, this increase is primarily due to a warmer fall followed by a warmer spring and minimal changes in the summer (Abendroth et al., 2019). The presence of the "warming hole" is expected to lessen in future years with the Midwest resembling other inter-continental regions in magnitude of warming (Kumar et al., 2013).

It is anticipated that by mid- and late-21st century, warmer temperatures and a decrease or seasonal redistribution of precipitation will reduce maize yields unless there are substantial adaptations provided through breeding and agronomy (Butler & Huybers, 2013; Jin et al., 2017; Urban et al., 2012). The magnitude of yield loss predicted may be overly severe due to the assumptions undergirding crop models regarding future climate such as the magnitude of evapotranspiration when vapor pressure deficits are higher (Basso & Ritchie, 2018). However, the direct impact of higher temperatures on crop development is more straightforward as the number of calendar days allocated to the grain fill period are projected to shorten by 15%-25% because of less time for starch deposition (Jin et al., 2017). In a warmer climate, crop development progresses more rapidly, with fewer calendar days needed to reach flowering (silking) and physiological maturity (Bassu et al., 2014; Hatfield & Prueger, 2015). Scientists expect farmers will adapt to these climatic changes and mitigate yield loss by planting longer season (also "later maturity" or "full season") hybrids that take advantage of the additional thermal time for grain fill (Howden et al., 2007; White et al., 2011). The use of longer season hybrids can theoretically sustain or increase maize yields under projected future climates compared to current hybrids, particularly when coupled with earlier planting (Easterling, 1996; Southworth et al., 2000). As such, hybrid maturity is often adjusted to longer season maturities in future yield simulations to reflect expected farmer adaptations (Bagley et al., 2015; Basso et al., 2015; Elliot et al., 2018).

Indeed, farmers are planting earlier over the past several decades in the Midwest (Kucharik, 2006; Sacks & Kucharik, 2011). With the change in climate to-date, it is plausible to assume farmers are adapting by selecting longer season hybrids because these outperform shorter season hybrids when planted earlier (Baum et al., 2020). However, the timing of planting is determined more by in-field operability, temperature, and precipitation rather than perfecting hybrid maturity placement (Kucharik, 2006; Pryor et al., 2014; Urban et al., 2012). Farmers use climate trends as a general timeframe for planting but then adjust for short-term weather forecasts and soil suitability as well as positioning the crop for a favorable climate during pollination and grain fill (Hatfield et al., 2011; Sacks et al., 2010). In contrast, hybrid choice is based on a hybrid’s yield potential, yield stability, adaptation to local climate and soils, resistance to expected pests, its fit within the overall production system, and the farmer’s attitude toward risk (Haigh et al., 2015; Letson et al., 2005; Macholdt & Honermeier, 2016). The majority of farmers make seed purchase decisions during the fall because of price incentives (Haigh et al., 2015) and are limited in spring adjustments regardless if it is an “early” or “late” spring.

The maturity of a hybrid is defined by individual seed companies using either relative maturity (RM) and/or growing degree days (GDD). Hybrid RM represents the relative length of “time” necessary for a hybrid to reach harvest-ready (20%-22%) moisture and is determined relative to a standard hybrid within the company, while hybrid GDD is the thermal time necessary to reach physiological maturity from planting (Carter, 1992; Dwyer et al., 1999b; Mahanna & Thomas, 2012). The GDD required to reach silking (R1) is also sometimes included in company literature because of variability among hybrids in the thermal transition from vegetative to reproductive development, although the ratio is approximately 1:1 (Abendroth et al., 2011; Nielsen et al., 2002). Farmers are encouraged to select a range of hybrids each year that differ by 10 RM units (approx. 200 GDD) to hedge risk from adverse weather since the crop would be in different developmental stages (Carter, 1992). It is recommended that the longest season hybrid mature approximately 10 days prior to a location’s average fall freeze date (Coulter, 2018; Hall & Reitsma, 2009).

Identifying if hybrid maturities have changed over time can be challenging given genetic and management advancements that confound or mimic visual changes associated with longer season hybrids. The exact date of physiological maturity, and therefore, the length of the crop cycle, is difficult to ascertain without kernel dissection. Visual cues such as leaf senescence and husk angle have proven useful (USDA NASS, 2012) but may now be outdated to a degree. Over a period of 25 years (1981–2005), a 12-day increase in time between planting and physiological maturity was identified using USDA NASS data along with earlier silking (Sacks & Kucharik, 2011). The increase
in time, particularly between silking and physiological maturity, was proposed to originate from the use of longer season hybrids. Vegetation indices derived from reflectance data have similarly revealed a lengthening (0.37 days per year) of the grain fill period across several Midwest states, with a change to longer season hybrids speculated as a potential reason (Zhu et al., 2018). While a longer grain fill period could arise from a change in hybrid maturity, it may also represent an extension of the functional grain fill period with no change in maturity. Plant breeders have reduced the anthesis-silking interval and sensitivity to stress over decades of selection such that current hybrids will now flower before the tassel is fully extended and pollen shed begins (Abendroth et al., 2019; Duvick, 2005; Lee & Tollenaar, 2007). In addition, longer maintenance of green leaf area (“stay-green”), increased post-anthesis nitrogen uptake and retention, and tolerance or resistance to pests all contribute to maize naturally senescing by avoiding premature stress-induced senescence (DeBruin et al., 2017; Duvick, 2005; Duvick et al., 2004; Lee & Tollenaar, 2007; Mueller et al., 2019; Thomas & Ougham, 2014; Tollenaar & Lee, 2006). The use of Bt transgenic hybrids has also reduced pest tunneling, resulting in sustained photosynthetic capacity for improved late-season stalk and ear health (Gatch & Munkvold, 2007). Finally, fungicide applications have become more routine between tasseling and early grain fill, thereby reducing foliar necrosis and potentially delaying senescence (Byamukama et al., 2013; Paul et al., 2011). These multi-faceted genetic and management changes introduce a challenge in deciphering changes to hybrid maturity apart from direct knowledge via sales data.

In this analysis, we address how changes in hybrid maturity correspond to climatic trends. Given the available dataset, it is possible to compare climatic trends and assess their relationships with socioeconomic variables. We seek to understand if farmers are using hybrid maturity as a potential adaptation strategy to climate change. Our research goals are threefold:

1. Explore a relationship between hybrid maturity and local thermal environment.
2. Determine if hybrid maturity choice has changed since 2000.
3. Identify the relationship between climate change and hybrid choice.

2 | METHODS

2.1 | Geographic coverage

In our analysis, we included 650 counties from 10 states in the US Midwest region (Illinois, Iowa, Indiana, Michigan, Minnesota, Missouri, North Dakota, Ohio, South Dakota, and Wisconsin). These states account for 68% of total maize acreage planted and 71% of maize produced in the United States in 2018 (USDA NASS, 2019a). The regional boundaries extend in latitude from 35.99°N to 49.00°N and longitude from 100.74°W to 80.51°W. The region represents rain-fed agriculture, with less than 5% of farmland irrigated except for Michigan and Missouri (9% and 6%, respectively; USDA NASS, 2017a).

2.2 | Hybrid data

Pioneer brand hybrid sales data between 2000 and 2016 were available on the county level from Corteva Agriscience (detailed records are not available before 2000). Because Pioneer hybrids are planted on approximately one-third of maize area globally (Begemann, 2015; Bonny, 2017; Fernandez-Cornejo, 2004), these data reasonably characterize regional preferences. Confidentiality requires that hybrid sales data are aggregated to the county in which the seed was delivered. It is likely that, for some counties, a proportion of the seed sold was transported to acres farmed in nearby counties.

Data were provided for 704 counties initially but reduced to 650 counties according to our selection procedure. Counties west of 100°W longitude were not included because of limited maize acreage (Figure S1) and a different sales structure, which limited county traceability. Most of the counties (n = 567) had complete records including all 17 years. However, 137 counties had 1–16 years of missing data. Fifty-four counties which were above the third quartile in missing data (12 years) were excluded. No discernable pattern was detected among the years missing in the remaining counties, and missing data were considered random. The standard deviation was calculated for hybrid maturity (GDD) in each county across the 17 years analyzed. Hybrid data that fell outside three standard deviations of the mean (44 of 55347 total observations, 0.08%) were excluded. Following these adjustments, hybrid data for 650 of 856 total counties in the region were used in this analysis: IA (n = 99 of 99), IL (n = 94 of 102), IN (n = 81 of 92), MI (n = 45 of 83), MO (n = 72 of 114), MN (n = 72 of 87), ND (n = 24 of 53), OH (n = 67 of 88), SD (n = 42 of 66), and WI (n = 54 of 72).

The hybrid sales data were summarized as percent sold per maturity group per county-year. The maturity groups were in 5 RM increments with a total of 15 RM groups for the region, from 70 to 140 RM. For example, the “100 RM” group included percent sales for hybrids sold in the 98, 99, 100, 101, and 102 RM categories. Only RM groups with a minimum of 0.2% sales per year were retained to discard extreme non-representative maturity groups. The sales across RM groups generally followed a normal distribution within a county-year except for areas with silage production. For example, the differing distributions for St. Clair, Illinois, which is predominately grain acreage, and Marathon, Wisconsin, which has silage and grain acreage, are shown in Figure S2. For each RM group, an approximation of the GDD necessary to reach physiological maturity from planting was provided by Corteva Agriscience; the relationship between RM and GDD is similar to previous literature (Dwyer et al., 1999b). The hybrids sold across the region ranged from 1740 to 3390 GDD, with differences between RM groups of 90–130 GDD.
For each county-year, hybrid RM and hybrid GDD (Hyb-GDD) were calculated as weighted means by multiplying percent sales by RM (or GDD; Figure 1). The range in hybrid RM sales per county was determined by interpolating the binned data to derive the RM at the 10th percentile and the 90th percentile and calculating the difference.

2.3 | Climate data

Daily temperature and precipitation data were obtained from the Iowa Environmental Mesonet at the county level from area-based averages of a 0.125° latitude by 0.125° longitude analysis grid (Iowa Environmental Mesonet [IEM], 2018). Precipitation data were summed for two periods: April and May (“spring”) and July and August (“summer”). These time periods were specifically chosen as they may relate to hybrid choice related to spring planting and grain-filling conditions. Heat stress was calculated based on days within the frost-free period that had temperatures above 30°C using the heat stress degree days (HSDD) model (Abendroth et al., 2019). Precipitation and HSDD values are the mean for 2000–2017.

2.4 | Calculating environmental GDDs

Thermal time was summed across the frost-free period for each county-year using the linear GDD model with a base temperature of 10°C (Gilmore & Rogers, 1958). The methods used to establish the frost-free period and calculate GDD within temperature boundaries of 10 and 30°C are detailed in Abendroth et al. (2019). The GDD model is simple compared to other thermal models used to model maize phenology, such as crop heat units (CHU) or general thermal index (GTI; Brown & Bootsma, 1993; Dwyer et al., 1999a; Kumudini et al., 2014). However, hybrid maturities were only provided in RM with conversion to GDD, and further converting these to CHU or GTI would require additional assumptions. For 2000–2016, the average length of the growing season for the region ranged from 954 to 2398 GDD and 126 to 219 calendar days (Figures S3 and S4).

Temperature data spanning two time periods were used for each county: 17 years (2000–2016) and 67 years (1950–2016). The 17-year period was used to calculate the mean thermal time environmentally available (Env-GDD) per county during the period in which sales data are available. The 67-year data were used for the long-term climate trend analysis as the 17-year data can be highly

**FIGURE 1** Weighted means of commercial hybrids sold in 650 counties during the 2000 to 2016 period as (a) hybrid relative maturity, (b) hybrid growing degree day (GDD°C) requirement for physiological maturity, (c) thermal overlap between hybrid GDD and environmental GDD, and (d) thermal absolute difference between environmental GDD and hybrid GDD.
influenced by outliers. The 67-year period was best fit using a linear regression model for each county across time.

The thermal time necessary for hybrids to reach maturity was assessed relative to the available thermal time of a particular county for the frost-free period. The relationship between Hyb-GDD and Env-GDD is defined as “thermal overlap” with 100% representing a county with identical values for each. Values less than 100% represent counties that use a portion of the available Env-GDD to grow the hybrids selected.

2.5 | Farm operation data

To aid in understanding hybrid maturity choice beyond climate, farm operational data were explored such as silage production, farm size, and end-use. The area harvested for maize grain and silage was compiled for each county from 2000 to 2016, and the ratio calculated between the two variables (Figure S1; USDA NASS, 2018). Silage data were not reported as frequently as grain acreage data and not at county scale in Illinois, Indiana, Missouri, and Ohio. Farm size data were obtained from USDA NASS (2017b). The mean farm size for each county was determined by aggregating across all farms that were greater than 72 ha (180 acres) to eliminate specialty farms that may not be commercial maize operations. Finally, two end-uses of maize grain were assessed: number of dairy cattle (USDA NASS, 2017c), and production capacity for ethanol plants using maize grain or cellulosic biomass as of May 2019 (Renewable Fuels Association, 2019). The number of dairy cattle were calculated based on the mid-point of each category reported in the Census of Agriculture (USDA NASS, 2017c).

2.6 | Statistical analysis

Two types of regression models were employed: (1) linear regression to detect temporal changes in Hyb-GDD, derive Env-GDD for the 67-year trend per county, and measure change in climatic and farm operation variables; and (2) nonlinear regression for fitting hybrid maturity, thermal overlap, and absolute thermal difference to latitude. The temporal trend for each county was analyzed with estimated marginal means fit to a linear regression model for Hyb-GDD, hybrid range, and overlap between Hyb-GDD and Env-GDD. Years were adjusted to begin at 0 rather than 2000 to provide a meaningful intercept. For the nonlinear regression models, the Akaike information criterion and Bayesian information criterion values guided by biological appropriateness were used to select the model with best fit among linear, quadratic, linear plateau, quadratic plateau, plateau quadratic, and bilinear (split-line) to observed data (Miguez et al., 2016). The change in Hyb-GDD obtained from the linear regression model was fit using a Fay–Herriot model accounting for spatial correlation among neighboring counties (Molina & Marhuenda, 2015). This model considers the spatial structure and accounts for differing variances due to data availability per county.

All data analyses, graphing, and model fitting were performed within the R statistical package using R Studio (version 3.5.0, R Core Team, 2018; RStudio Team, 2016) with data migrated to and from SQLite (Hipp et al., 2015). Numerous packages were used in addition to base R as listed in Supplementary Information (Appendix S1).

3 | RESULTS

3.1 | Relationship between hybrid maturity and local thermal environment

Between 2000 and 2016, across all counties in our analysis, mean hybrid maturity ranged from 76 to 116 RM or 1038 to 1555 GDD (Figure 1a,b). Northern counties had mean hybrid maturities that required approximately 500 GDD less than those grown in southern counties. Most of Iowa, Illinois, Indiana, Missouri, and Ohio had similar hybrid maturities ranging from 1400 to 1550 GDD. The latitudinal range of a hybrid maturity group narrowed from southern to northern counties. For example, hybrids with 90–95 RM are primarily grown in a narrow band of counties before the response shifts to another maturity group. The range in hybrid maturities grown is much narrower than the available Env-GDD which ranges from 1067 to 2398 GDD (Figure S4).

The thermal overlap between Hyb-GDD and Env-GDD ranged from 63% to 106% south to north (Figure 1c). Northern counties had a substantially greater overlap between Hyb-GDD and Env-GDD than southern counties, and four counties in the far northeast of our study region exceeded the available Env-GDD with their hybrid maturity choice. This difference in overlap results in southernmost counties having up to 860 GDD more than necessary to produce the chosen hybrids (Figure 1d). The southernmost counties had nearly as many additional GDD as the northernmost counties for their entire frost-free period.

The county values shown in Figure 1 were analyzed relative to latitude to identify overall statistical relationships (Figure 2). The relationships between hybrid RM and hybrid GDD to latitude were similar, although the selected models were the plateau–quadratic for hybrid RM and bilinear for hybrid GDD (Figure 2a,b). Hybrid RM and GDD were maximized at the southernmost latitudes (lower x-axis values) and minimized at the northern latitudes (higher x-axis values). A bilinear relationship was fit between thermal overlap and latitude with the amount of overlap increasing as latitude increased (Figure 2c). The breakpoint (xs) for thermal overlap was at 42.8° latitude, counties north of which experienced a fourfold reduction in slope. A quadratic–plateau best described the relationship between the absolute difference of Env-GDD and Hyb-GDD with fewer additional GDD available as latitude increased (Figure 2d). The breakpoint for the thermal absolute difference was 45.5° latitude with a base plateau of 64 GDD for counties north of 45.5°. The breakpoint (xs) among Figure 2a–c ranges from 40.1° to 42.8° latitude.
Hybrid maturities are shown in Figures 1 and 2 as weighted means, although, notably, the average range in RM was 9.3 with it varying by county from a minimum of 4.3 to a maximum of 21.8 (Figure S5). This range represents the difference between the shortest and longest maturity chosen per county. The range in hybrid maturity generally increased from south to north, and as the proportion of silage acreage increased relative to grain acreage.

### 3.2 Hybrid maturity changes since 2000

The majority of counties had shorter season hybrids in 2016 than in 2000. The mean hybrid maturity (GDD) for each year reveals a trend of shorter season hybrids chosen (Figure S6) and greater temporal fluctuations occurring in peripheral counties. The change in hybrid maturity was analyzed using non-spatial (Figure 3a) and spatial (Figure 3c) methods with the latter accounting for the correlation and heterogeneity in variance among counties, as shown in the confidence intervals (Figure 3b). Significance values for the non-spatial model were generated to determine if the annual rate of change was non-zero, with 61 counties increasing and 263 decreasing, resulting in half of the counties \(n = 324\) of 650) with a significant change at \(p \leq 0.10\) (Figure 3b). The spatial Fay–Herriot model provided a more conservative rate of change for counties, particularly those with smaller sample sizes. The output from the spatial model will be used in further analyses because of less variation and in consideration of correlation among neighboring counties. The rate of change in Hyb-GDD, when summed across the 17-year period, ranged from −91 GDD to +69 GDD and median of −14 GDD. Counties within the central corridor of the region primarily experienced a reduction in hybrid maturity while those counties along the northern and southern peripheries were unchanged or increased.
3.3 Relationship between climate change and hybrid choice

The changes in Hyb-GDD were evaluated relative to the long-term (67-year) climate trend quantified using Env-GDD as well as precipitation and heat stress. If the choice of Hyb-GDD were driven solely by a change in temperatures during the growing season, quadrants 1 or 3 would be most populated in Figure 4, along the dashed 1:1 line. Instead, the majority of counties (61%; \( n = 395 \) of 643) were sorted into quadrant 4, which represents an increase in Env-GDD and a decrease in Hyb-GDD. Counties with matching signals in environment and hybrid are in quadrants 1 (26%; \( n = 166 \) of 643) and 3 (11%; \( n = 72 \) of 643). Thus, only 37% of counties (\( n = 238 \) of 643) had the change in Env-GDD and Hyb-GDD in the same direction (either positive or negative). Across all quadrants, the amount of change in Hyb-GDD was often greater than that of Env-GDD.

Considerations beyond thermal availability were examined, such as whether hybrid maturities have been adjusted to accommodate for increasingly frequent wet springs, avoidance of mid-summer precipitation shortfall and/or heat stress mid-summer, accommodation for large farm operations, and fall delivery to ethanol biorefineries or dairy producers. Spring (April, May) precipitation ranged from 93 to 280 mm across the region (Figure 5a) but a meaningful relationship to change in hybrid maturity was negligible (Figure 5b). Summer
(July, August) precipitation ranged from 114 to 230 mm (Figure 5c) and areas with less absolute rainfall trended toward shorter Hyb-GDD (Figure 5d). HSDD units were relatively low across most of the region except for southern and western counties which had up to 111 HSDD (Figure 5e). Counties with greater heat stress had a reduction in hybrid maturity. A divergent response in Hyb-GDD...
existed in counties with the highest heat stress (">100"); this was due to counties in southeast Missouri lengthening Hyb-GDD and southwest Missouri shortening Hyb-GDD (Figure 5f). Finally, farm size ranged from 141 to 1520 hectares with the majority of the Midwest less than 350 ha (data not shown; Figure 5g). Most counties had no difference in Hyb-GDD by farm size except large farms located in North Dakota and South Dakota which had a reduction (Figure 5h).

The change in Hyb-GDD was also assessed regarding economic and end-use considerations such as whether the grain is transported to ethanol biorefineries or allocated for dairy consumption (Renewable Fuels Association, 2019; USDA NASS, 2017c). There were 139 ethanol biorefinery plants in 123 counties with production per county ranging from 42 to 2215 million L year$^{-1}$ with a mean of 370 million L year$^{-1}$ (Figure 6a; Renewable Fuels Association, 2019). Ethanol plants are shown by their physical location, although grain can easily be transported from outside the county borders; a 64 km transport distance has been used in other analyses (Shapouri et al., 2003). Dairy cattle are located in 552 counties but 141 are quite

![Graphs showing ethanol production per county, dairy cattle per county, change in hybrid GDD by ethanol production, and change in hybrid GDD by dairy cattle.](image)

**Figure 6** End-use variables of potential influence on hybrid choice include (a) total production from ethanol biorefinery plants, and (b) number of dairy cattle. The corresponding annual rate of change in hybrid growing degree day (GDD°C) is shown relative to (c) ethanol production categories, and (d) number of dairy cattle categories. Ethanol production capacity is in million L year$^{-1}$ and dairy cattle are number of animals.
small (<5000 cattle); the 411 counties greater than 5000 represent the majority of dairy cattle in the region (Figure 6b). As ethanol production in a county increases, hybrid maturity shortened and the range in hybrid maturity narrows (Figure 6c). The opposite trend exists with dairy cattle in which counties with higher populations have greater range and are lengthening in hybrid maturity (Figure 6d).

4 | DISCUSSION

4.1 | Relationship between hybrid maturity and local thermal environment

We found a sustained decrease in thermal overlap from north to south with an absolute difference of up to 860 GDD in southern Midwest counties. If hybrid maturity choice was only driven by available thermal time to reach physiological maturity, the overlap would be the same across all counties (Figures 1c and 2c). Instead, the gap widened between Hyb-GDD and Env-GDD from north to south. The additional GDD were beyond what was necessary for growing the maize hybrids chosen, and the remainder of the growing season may be used for in-field dry-down, carrying out field operations, or as a fallow period (USDA NASS, 2019a). The thermal overlap between Hyb-GDD and Env-GDD increased at a linear rate of 0.6% north of 42.8° latitude and decreased by 4.6% in the south (Figure 2c). The thermal time available to grow a crop became increasingly less critical from north to south in the study region. Northern counties experienced very few additional GDD beyond what was required for reaching crop maturity with a difference of only 64 GDD, while southern counties had ample GDD (Figure 2d). These relationships emphasize that hybrid choice is not based solely on heat availability.

There were northern counties with hybrid maturities that had thermal requirements beyond what was environmentally available, resulting in thermal overlap values above 100% (Figures 1c and 2c). A sizable proportion of land use in northern counties, however, was allocated to maize silage (Figure S1), which is harvested prior to physiological maturity. Silage harvest occurs at the mid-R5 (reproductive 5 or “dent”) stage or approximately the 2/3 “milk line” (Filya, 2004). This earlier harvest reduces the thermal requirement by approximately 200 GDD from that required for maturity (Abendroth et al., 2011) which explains the high amount of overlap. Farmers in these counties also chose a wider range of hybrid maturities (Figure S5) likely due to multiple end-uses such as grain, silage, or grain ensiled at ~35% moisture.

4.2 | Hybrid maturity changes since 2000

The absolute change in Hyb-GDD during this 17-year period (~91 GDD to +69 GDD) represents only a fraction of the GDD needed to reach physiological maturity. But it was a consistent trend that is a clear departure from widespread expectations. Counties that have shortened Hyb-GDD are consistently the highest yielding areas of the Midwest (USDA NASS, 2019b). These high yields are not the result of maximizing hybrid maturity length. High-yielding, long-season hybrids that were previously very popular can lose their market advantage to shorter season hybrids if the latter are supported by intensive local breeding efforts. Current maize breeding programs are mostly commercial with breeding objectives defined according to farmers’ needs and preferences. Private maize breeding programs ascertain which qualities are important among current and emerging markets through market development research focused on current clientele (Cobb et al., 2019). Therefore, it is not surprising that as maize croplands have expanded into the northwest for decades (Laingen, 2017; Lin & Huang, 2019), the portfolio of products available for these northern counties has increased. Yield gains associated with shorter season hybrids have been steeper than for longer season hybrids over the past three decades (Assefa et al., 2017). Also, yields of longer season hybrids do not necessarily always outperform shorter season hybrids in the Midwest as variability among hybrids within a maturity group is substantial and greater than the mean difference among maturity groups. For example, yields averaged across many hybrids in 2018 by the Iowa Crop Improvement Association Hybrid Performance Tests were nearly identical between “early” and “full” season hybrids when evaluated on a district level (Iowa Crop Improvement Association [ICIA], 2018). In research conducted by Baum et al. (2019) in Iowa, yield variability across planting date and hybrid maturity was only minimally attributed to hybrid maturity. Similar yields were obtained between shorter and longer season hybrids as long as a minimum of 648 GDD were obtained during grain fill. However, hybrid maturity is a more significant consideration in yield variability for areas north of Iowa (Jescke, 2019).

There are notable pockets of counties in the north and south that lengthened Hyb-GDD. Most of the county’s trend toward longer hybrid maturities were north of 42.8° latitude (Figure 2c). These northern counties are gaining thermal time considerably more rapidly than other areas (Abendroth et al., 2019). Given the heat limitations in these counties for growing maize, we expect continued lengthening to occur to maximize thermal overlap. Some southern counties in the states of Missouri, Illinois, Indiana, and Ohio also trended toward longer maturities. The motivation for this lengthening, however, may be different than in the northern counties. Based on communication with Pioneer agronomists, this may be associated with drought-tolerant germplasm options within specific maturity groups that were chosen for traits rather than hybrid maturity. The counties in southwest Missouri were notably distinct from other southern counties as they chose shorter hybrid maturities. This is likely a heat avoidance strategy to shift the grain fill period earlier in the season (Henry & Krutz, 2016). The heterogeneity in hybrid maturity changes across the Midwest reiterates the need for regional-based climate adaptation strategies with high specificity of local challenges.

Theoretically, counties along the periphery of the Midwest could serve as indication of what further inset counties may experience in the future. This is problematic though when applied to hybrid choice because peripheral counties have a lower volume
of hybrids sold, resulting in higher variation for trend analysis. This variability is evident in North Dakota and South Dakota, where the changes between counties were much larger than in Iowa (Figure 3a). In these north-western states, we know that some farmers likely operate across several counties or possibly state lines as the average farm size is three to seven times that of the other Midwest states (USDA NASS, 2011). Farmers in these states also continue to increase artificial subsoil drainage and replace grasslands and small grain crops with maize and soybean (Castellano et al., 2019; Johnston, 2014; Lin & Huang, 2019; Wimberly et al., 2017) and therefore, may still be learning what hybrid maturities are optimal for their operations.

4.3 Relationship between climate change and hybrid choice

In contrast to widespread expectations (Bagley et al., 2015; Basso et al., 2015; Elliot et al, 2018), US Midwest farmers are planting shorter hybrid maturities despite warming temperatures. We did not find evidence that hybrid choice has been driven by temperature-based climate change in most areas of the Midwest between 2000 and 2016. The magnitude of warming which has occurred has exerted little control on hybrid choice. The regional cooling from the climatic “warming hole” has caused observed gains in thermal time to be primarily from the fall and secondarily the spring (Abendroth et al., 2019). This additional allocation of Env-GDD, in northern counties predominately and secondarily in southern counties, would seem to be a perfect test case for lengthening Hyb-GDD maturities to capitalize on an extended grain fill period. Yet this has not occurred widely to-date. Furthermore, in southern counties where Hyb-GDD has lengthened, it has not lengthened to the same degree that the climate has warmed (Figure 4). It is only in some northern counties where the relationship between change in Hyb-GDD and change in Env-GDD is more closely aligned.

A longer maturity hybrid has been shown to generally result in higher yields when soil water availability is not limited during the season. But, if the allotment of available water is used primarily during vegetative development, yield loss can occur due to a shortfall during flowering and grain fill (Liu & Basso, 2020; Messina et al., 2011; Tardieu, 2012). A shortening of hybrid maturity will reduce the length of both vegetative and reproductive developmental periods. Given that yield potential is established during the vegetative period but realized during the reproductive period, maximizing both is a balance and a challenge. Heat exposure has less impact during the vegetative period but results in kernel abortion and reduced starch accumulation when high temperatures and drought stress occur during silking and grain fill (Hatfield & Prueger, 2015). In areas prone to precipitation shortages or heat stress, shortening the hybrid maturity may be a risk-averse strategy. This strategy could be especially useful in areas with high summer temperatures and limited soil water storage capacity or high evapotranspiration (Liu & Basso, 2020).

Depending on the extent and seasonality of future warming, hybrid maturity adaptations for much of the Midwest may be based more on optimizing logistics and minimizing yield loss from mid- and late-season stresses rather than maximizing the growing season as speculated. Adaptation strategies that align the growing cycle of maize with the optimum temperature range are essential (Bassu et al., 2014) whether or not the full growing season is utilized. However, other considerations such as wetter falls coupled with wetter springs that have occurred over much of the Midwest in 2018–2019, for example, may override the importance of hybrid maturity. Farmers must ensure that the crop can be feasibly planted and harvested. It is highly plausible that small, incremental changes noted in long-term climate trends for temperature or precipitation are of less concern to farmers than outlier years and risk avoidance strategies.

Adaptation strategies for counties that have a substantial amount of additional Env-GDD (Figures 2c and 3c) may choose to increase cropping frequency and diversity rather than lengthening their hybrid maturities. Depending on heat and soil moisture availability, this could involve double or triple cropping across 2 years for grain and/or biomass (Meza et al., 2008; Moore & Karlen, 2013; Seifert & Lobell, 2015).

In addition to environmental factors, farm size, the use of maize for dairy cattle and ethanol production may be motivating changes in the region more than climate. A shortening in hybrid maturities has occurred in areas with greater farm size (Figure 5) and areas with ethanol production (Figure 6). The preference for greater in-field grain dry-down for direct transport to ethanol biorefineries or to reduce on-farm drying may be motivating the observed reduction in hybrid maturity. The additional time for fall tillage and fertilizer application for spring readiness may also encourage the choice of shorter maturities. There is also evidence the harvesting of maize for silage and feed to dairy cattle resulted in a lengthening of hybrid maturity to maximize the vegetative biomass (Wilkens et al., 2015). These influencing factors warrant further analyses. Efforts to couple local economic drivers with environmental factors as important feedbacks in farmer decision-making appear key in discerning plausible adaptation strategies.

A third to half of the farmers in the “Corn Belt” plan to change management practices in response to climate change such as the use of no-tillage, cover crops, and tile drainage (Roesch-McNally et al., 2016). Therefore, many farmers appear to be highly responsive to changes in climate and are planning for potential equipment or infrastructure investments. The choice of hybrid is a more agile adaptation strategy with only an annual investment by farmers and can, therefore, change quite rapidly as the climate changes. However, breeding for particular maturities and other attributes is less agile and may take a decade of planning. Hybrid choice by farmers paired with ongoing hybrid improvement through both traditional plant breeding and biotechnology will be critical areas of research moving
forward (Varshney et al., 2011) as we identify the most robust climate adaptation strategies.

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**DATA AVAILABILITY STATEMENT**

This research uses proprietary industry sales data which are not shared.

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