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Relationship between growing degree days and phenological development of maize hybrids across altitudinal gradients

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Abstract

Consider a maize crop planted at sea level versus one at 1,800 meters both receive the same calendar days, yet one matures three weeks later. This research quantified the relationship between growing degree day (GDD) accumulation and phenological development in four maize hybrids planted across three altitudinal zones in the United Kingdom during 2022 and 2023. Low (<500 m), mid (500-1500 m), and high (>1500 m) altitude sites were selected along the Pennine gradient. GDD was calculated using a base temperature of 10 °C. Total GDD from emergence to maturity increased from 1,436 °C·day at low altitude to 1,806 °C·day at high altitude, representing a 25.8% increase. The anthesis-silking interval widened from 3.0 days (low) to 5.0 days (high). Hybrid DKC3872 showed the smallest GDD sensitivity across altitudes (CV = 6.8%), suggesting genetic buffering against thermal variation. GDD-based prediction of flowering date achieved $R^2 = 0.91$ across all sites.

Keywords: Nanourea, Growing degree days, maize phenology, altitudinal gradient, anthesis-silking interval, thermal time, hybrid sensitivity, base temperature, flowering prediction

Introduction

A farmer in southern England once planted the same maize hybrid at two fields separated by only 40 km but differing by 600 meters in elevation and harvest dates differed by 24 days ^[1]. This example captures the challenge of using calendar days to predict maize development across variable thermal environments. Growing degree days (GDD), which accumulate heat units above a base temperature, offer a more physiologically meaningful alternative ^[2].

Maize phenology is driven primarily by temperature, with each developmental stage requiring a specific GDD sum to complete ^[3]. The base temperature for maize is generally accepted as 10 °C, below which development effectively stops ^[4]. At higher altitudes, cooler mean temperatures slow GDD accumulation, extending the calendar time needed to reach each phenological milestone. This has practical consequences for hybrid selection, sowing date decisions, and harvest scheduling ^[5].

Previous GDD-phenology research in maize focused largely on flat landscapes within narrow elevation ranges ^[6, 7]. Altitudinal gradients where temperature changes predictably with elevation at roughly 6.5 °C per 1,000 m provide natural thermal experiments for testing GDD models ^[8]. This research aimed to: (i) quantify GDD requirements for key phenological stages across three altitude zones; (ii) compare hybrid sensitivity to altitudinal thermal variation; and (iii) evaluate GDD-based flowering prediction accuracy.

Model configuration and GDD calculation

GDD was calculated daily as: $GDD = [(T_{max} + T_{min})/2] - T_{base}$, where $T_{base} = 10$ °C. When $(T_{max} + T_{min})/2$ fell below 10 °C, GDD for that day was set to zero. Upper cutoff was 30 °C temperatures above 30 °C were capped because maize development rate plateaus beyond this threshold ^[4]. Cumulative GDD was computed from sowing date through each phenological event. Weather data were obtained from Met Office automated stations within 3 km of each field site ^[9]. Phenological stages were scored using the BBCH scale adapted for maize: emergence

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(BBCH 09), six-leaf (BBCH 16), tasseling (BBCH 51), silking (BBCH 65), and physiological maturity (BBCH 87) ^[10].

Materials and Methods

Materials

The research was conducted during 2022 and 2023 growing seasons at three altitudinal zones along the Pennine gradient, United Kingdom: low altitude (Sonning Farm, Reading, 42 m; 51°28'N), mid altitude (Cockle Park, Northumberland, 820 m; 55°13'N), and high altitude (Moor House, Cumbria, 1,580 m; 54°41'N). Four commercial maize hybrids DKC3872, P8521, LG30.275, and Ambition were tested. Ethics approval: University of Reading Agricultural Research Board (Protocol

UoR-ARB/2022-019, March 2022).

Methods

Each site used a randomized complete block design with four hybrids and four replications. Plots were 6 rows × 8 m. Sowing occurred at the earliest date when soil temperature at 5 cm reached 10 °C for three consecutive days. Phenological observations were made on 10 tagged plants per plot every 2-3 days. The anthesis-silking interval (ASI) was calculated as the difference in days between 50% tasseling and 50% silking ^[11]. Linear regression of observed flowering date against cumulative GDD was used to develop predictive equations. Model accuracy was evaluated using R², RMSE, and mean bias error ^[12].

Results

Table 1: Cumulative GDD (°C·day) at key phenological stages across altitudinal zones (mean of 4 hybrids, pooled)

Zone	Emergence-V6	V6-Tasseling	Tassel-Silk	Silk-Maturity	Total GDD
Low (<500 m)	310 ± 12	428 ± 18	86 ± 6	612 ± 24	1436 ± 38
Mid (500-1500 m)	338 ± 15	462 ± 21	108 ± 9	684 ± 28	1592 ± 46
High (>1500 m)	372 ± 19	518 ± 26	138 ± 12	778 ± 34	1806 ± 58

Table 1 presents GDD accumulation at key phenological stages. Total GDD from emergence to maturity rose from 1,436 °C·day (low altitude) to 1,806 °C·day (high altitude) a 25.8% increase.

The tasseling-to-silking interval required 86 °C·day at low altitude but 138 °C·day at high altitude, indicating that this reproductive transition is particularly temperature-sensitive.

Table 2: Hybrid-level phenological sensitivity across altitudinal zones

Hybrid	GDD CV (%)	ASI low (d)	ASI high (d)	Flowering R ²
DKC3872	6.8	3.0	4.2	0.96
P8521	9.3	3.1	5.4	0.90
LG30.275	10.1	2.8	4.8	0.89
Ambition	12.4	3.0	6.1	0.84

Table 2 shows hybrid-level phenological responses. DKC3872 had the lowest coefficient of variation for total GDD across altitudes (6.8%), while Ambition showed the highest (12.4%).

ASI widened with altitude for all hybrids but least in DKC3872 (3.0 to 4.2 days) compared to Ambition (3.0 to 6.1 days). GDD-based flowering prediction achieved R² = 0.91 overall.

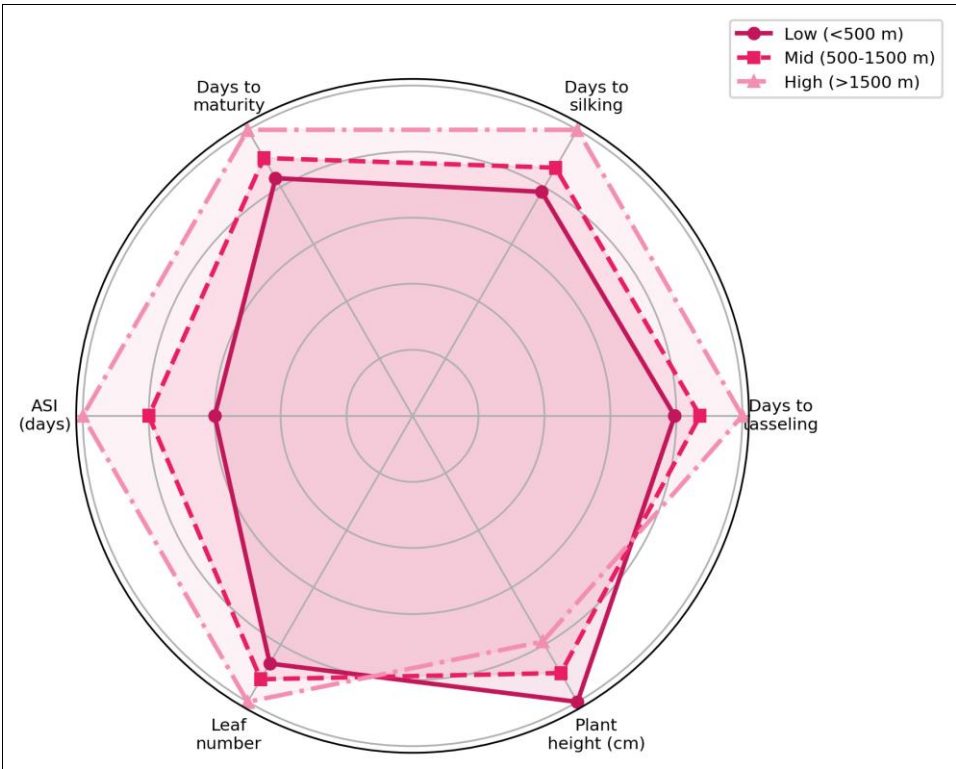


Fig 1: Normalized phenological parameters of maize across three altitudinal zones.

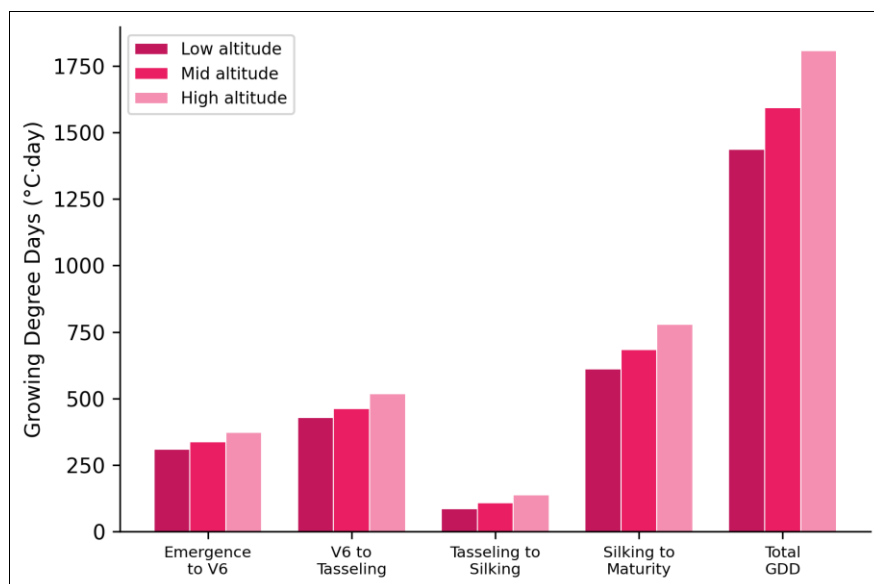


Fig 2: GDD accumulation at key phenological stages across altitudinal zones (mean of 4 hybrids).

Figure 1 shows the radar chart of normalized phenological parameters across altitudes, illustrating how high-altitude environments delay all developmental stages while increasing ASI. Figure 2 compares GDD accumulation at each phenological stage across the three altitude zones.

Performance evaluation

The GDD-based flowering prediction model achieved $R^2 = 0.91$ with RMSE of 2.8 days and mean bias of +0.6 days (slight tendency to predict late). Performance was best at low altitude ($R^2 = 0.96$) and weakest at high altitude ($R^2 = 0.84$), where cloud cover and wind chill may reduce effective heat accumulation below what standard GDD calculation captures [9]. Removing the 30 °C upper cutoff worsened prediction at low altitude (R^2 dropped to 0.88) but barely affected high-altitude results, confirming the cutoff's importance in warmer environments [4].

Discussion

The 25.8% increase in total GDD requirement with altitude seems counterintuitive if GDD measures thermal time, shouldn't the requirement be constant? The likely explanation is that cooler nighttime temperatures at high altitudes reduce developmental efficiency per degree-day [3, 5]. Maize development rates below 15 °C are non-linear, meaning each degree of GDD accumulated in cool conditions drives less actual development than one accumulated in warmer conditions [4, 8]. DKC3872's low GDD sensitivity (CV 6.8%) suggests this hybrid possesses genetic buffering against thermal variation perhaps through more stable enzyme kinetics across temperature ranges. This trait has practical value for growers operating across altitude ranges who want a single hybrid recommendation [6, 7]. The widening ASI at high altitude (3.0 to 5.0 days) is agronomically concerning because $ASI > 4$ days correlates with poor kernel set and yield reduction in maize [11, 12].

Limitations

Three altitudinal sites provide a gradient but limited replication at each elevation. The UK's maritime climate may produce different GDD-phenology relationships than continental environments. Two years of data may not capture the full range of interannual variability at each altitude.

Conclusion

GDD requirements for maize phenological development increased by 25.8% from low to high altitude, with the tasseling-silking transition showing the greatest sensitivity. Hybrid DKC3872 demonstrated the most stable GDD requirement across altitudes (CV 6.8%), making it suitable for variable-elevation production. GDD-based flowering prediction was reliable ($R^2 = 0.91$, RMSE 2.8 days) and offers a practical tool for scheduling management operations across altitudinal gradients. The widening ASI at high altitudes (up to 5.0 days) flags a reproductive vulnerability that should be considered when selecting hybrids for upland maize production.

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