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Effect of daily thinning on biweekly increment of growth and yield of maize (*Zea mays* L.) in mountainous agroecosystem

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Abstract
Maize (*Zea mays* L.) growth and yield are severely affected due to intraspecific competition and agroclimatic conditions when cultivated with high plant densities. Field trials comprising four daily thinning patterns (0, 0.5, 1.0, &1.5% till silking) carried out in three consecutive years (2019–2021) using RCBD experimental design consisting of three replicates. Growth variables, dry matter allocation and growth rates in maize were examined during five biweekly periods starting from the emergence (15, 30, 45, 60 and 75 days after emergence, DAE) till silking whereas yield parameters i.e., biological yield, economic yield, and sustainability yield index (SYI) were recorded. Biweekly increase in growth variables, dry matter partitioning and growth rates of maize differed significantly due to the influence of daily thinning computed for the periods from 31 to 45, 46 to 60 and 61 to 75 DAE but the same parameters didn't differ significantly during the first two biweekly periods (1–15 & 16–30 DAE). Increase in growth variables, dry matter distribution, absolute growth rate (AGR), yield and SYI was the greatest where maize was established with 1% daily thinning. This increase in growth and dry matter partition observed highly associated to economic yield and biological yield. Current research highlighted that 3, 4^{th,} and 5th biweekly periods are the most critical stages and daily thinning of 1% is suggested for higher and sustainable economic and biological returns from high density broadcasted maize.

Keywords Corn, Daily thinning, Fodder maize, High-density planting, Mountainous agroecosystem, Plant population

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Introduction

Optimization of plant density and daily thinning in maize (*Zea mays* L.) is a great challenge when it is grown for both grain and fodder simultaneously [1, 2]. In hilly areas, agricultural land is scanty and enough land is not available where maize can be cultivated separately for both food and fodder purposes to accomplish human and animal needs [3, 4]. Being a C_4 plant, maize serves as major source of grain and fodder availability to ensure its accessibility in harsh and long winter periods in high mountainous areas [5]. In this connection, farmers usually establish a high-density maize crop and soon after germination start thinning by harvesting a portion of plants from the field. These thinned fresh plants are chopped and fed to livestock (cow, goat & sheep) on daily basis.

Human population in hilly areas is also multiplying and exerting more pressure on scarce resources available in these hardship terrains. This has amplified the challenge of food security due to multiplying needs of the inhabitants for food and fodder commodities [6]. The food security challenge necessitates the widening of food sources through optimization and diversification of food crops and livestock-based food production systems [7]. Extension of crop cultivation area horizontally is difficult in hilly areas, but productivity of agricultural land can be enhanced through vertical expansion (per unit area) to decrease current and expected food and fodder insecurity threats in mountainous valleys [8]. In the study area, livestock production is one of the major sources of income for about 43% rural inhabitants where maize serves as an important source of fodder availability [9, 10]. Premature maize plants are fed to livestock as chopped raw grass that provides a good quality fodder with high palatability containing approximately 9–10% crude protein, 60–64% neutral detergent fiber, 38–41% acid detergent fiber, 23–25% hemi-cellulose, and 28–30% cellulose on dry weight basis [11].

Maize shows varied growth and productivity owing to the effect of changing annual climatic situations at different altitudes and planting densities [12]. Variables related to plant growth at different development stages and yield can be examined through observing periodic dynamics in these parameters [13]. Plant density and altitude together determine the microclimate that significantly affect the growth at different development stages of the crop [14]. Photosynthetic efficiency of plant leaves is severely affected because of variation in micro-environment that leads to variability of growth and dry matter assimilation into different plant components through changing physiological reactions happening within the plant body. Periodic growth, development, yield parameters, and indices of plants cultivated in low plant density compared to high plant density conditions respond differently starting from germination to maturity stage of the crop [15–18]. Likewise, growth and yield outputs of crops cultivated at low altitude vary significantly compared to those cultivated at high elevated lands [19]. Conversion of primary photosynthetic assimilates into plant structural material differ due to night temperature dynamics [20]. A decrease in diurnal temperature results low rate of photosynthetic conversions into plant body parts and vice versa for the high diurnal temperature situations [21]. Due to prevalence of humid and temperate environmental conditions, dry biomass productivity of crop vary to a significant level owing to changing environmental scenarios associated with land topography or altitude [22].

High plant density enhances interception of solar radiation but augments intraspecific competition among the plants for available resources [23]. This competition further induces abiotic and biotic stresses which lead to significant reduction of leaf area, chlorophyll content, grain yield and disease incidence owing to favourable microclimate [24]. Due to this stress, photosynthetic efficiency is compromised thereby decreasing the absolute growth rate and biological productivity of the crops [25–27].

Growth, dry biomass partition and grain yield of a plant are good indicators of variability due to annual dynamics in weather, altitude, and plant densities [28]. Variation of plant growth and dry matter partitioning have been examined by others [27, 29], but variation in growth variables in a narrow temporal resolution (biweekly periods) to highlight the contributing factors is still missing. Significant decrease in crop growth and productivity due to high plant density is clearly understood from other research studies [1] but none of the previous research studies explained the biweekly variation of growth, development, and dry matter partitioning of maize when grown with daily thinning practices at different altitudes.

Thinning effects have been reported by many researchers in different agroclimatic conditions but there is absence of studies related to its possibility in temperate and at higher altitudes. Moreover, temporal examination of growth variables of maize for different daily thinning intensities at different altitudes have not been reported by other researchers. Hence, objective of this research was to generate information pertaining to the influence of daily thinning practice on growth and yield of remaining plants of high density maize to highlight appropriate thinning intensity to support food security and fodder availability in mountainous agroecosystem. Further, this research highlights the biweekly periods significantly affecting the growth variables and productivity of maize established with different thinning intensities by recording biweekly variation after the crop emergence.

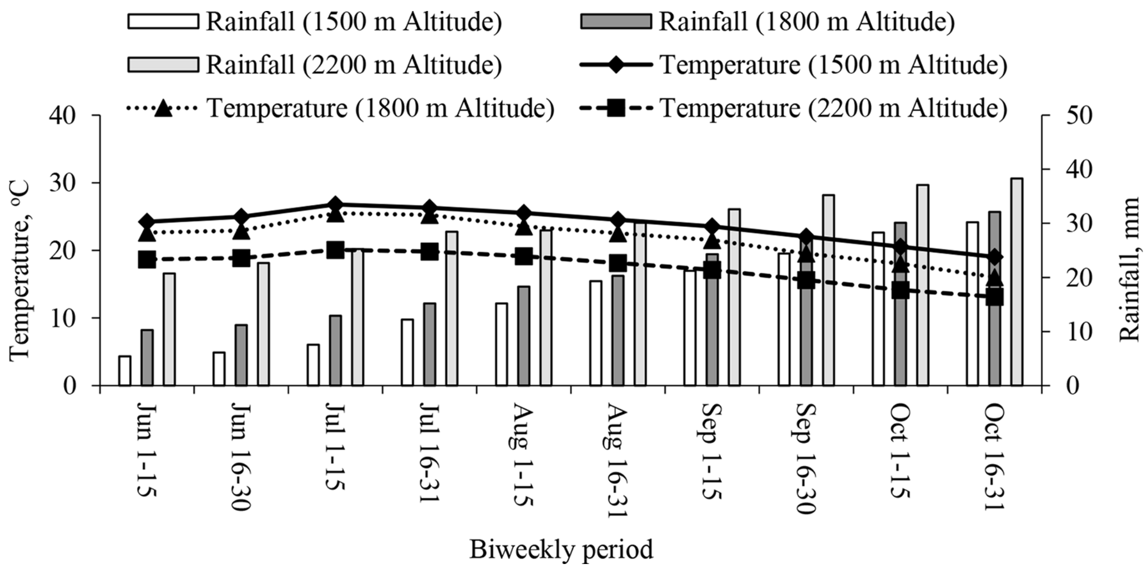

Fig. 1 Biweekly variation of rainfall and temperature at study sites during the cropping season

Table 1 Soil properties of experimental locations

Parameter	**Unit**	**Altitude, m and Year**								
		1500			**1800**			**2200**		
		2019	**2020**	**2021**	**2019**	**2020**	**2021**	**2019**	**2020**	**2021**
pH	-	6.52	6.60	6.45	6.35	6.45	6.50	6.25	6.25	6.25
EC	dS m^{-1}	0.43	0.63	0.64	0.30	0.43	0.43	0.34	0.36	0.33
Sand	%	54.00	50.00	47.00	62.50	55.50	52.50	60.00	56.00	54.00
Silt	%	15.50	14.50	19.50	19.50	25.50	28.50	22.50	24.50	28.50
Clay	%	29.50	34.50	33.50	18.00	19.50	18.50	17.50	19.50	17.50
OM	%	1.95	2.10	2.25	1.90	2.00	2.10	2.30	2.40	2.80
N	mg kg^{-1}	13.00	17.00	19.00	12.00	15.00	16.00	13.00	16.00	17.00
P	mg kg^{-1}	18.44	16.50	13.70	15.23	14.94	10.20	11.50	10.85	10.05
K	mg kg^{-1}	112.52	105.64	98.70	90.45	86.33	83.24	75.30	60.09	53.48
Ca	mg kg^{-1}	1130.00	1111.00	1106.00	1050.00	1018.00	1005.00	980.00	950.00	905.00
Mg	mg kg^{-1}	305.70	303.70	303.50	285.80	279.90	275.50	220.80	215.00	212.20
Cu^{2}	mg kg^{-1}	5.22	4.50	4.40	3.50	2.65	2.64	2.42	2.40	1.80
Fe^{3+}	mg kg^{-1}	4.74	4.62	4.26	4.80	4.65	4.55	4.30	4.43	4.20
Mn^{2+}	mg kg^{-1}	3.34	3.32	3.16	4.52	3.05	4.24	3.50	3.42	3.25
Zn^{2+}	mg kg^{-1}	1.23	1.34	1.52	1.42	1.15	1.34	1.40	1.42	1.35
Textural class	-	Sandy Clay Loam			Sandy Clay Loam			Sandy Loam		
Soil Type	-	Alfisols			Alfisols			Inceptisols		

Note: OM_ organic matter, EC_ electrical conductivity, N_ nitrogen, P_ phosphorus, K_ potassium

Materials and methods

Study area climate

To assess influence of year, altitude and daily thinning of high-density maize, research trials were conducted in Summer cropping season of years 2019, 2020 and 2021 at three altitudes, i.e., 1500 m, 1800 m and 2200 m above average sea level corresponding to geographical coordinates of 35.9202° N, 74.308° E, 36.316° N, 74.650° E, and 36,102° N, 73.460°E, respectively, which were experiencing varied agro-climates (Fig. 1). Soil samples were procured from experimental locations by digging soil till 30 cm depth and were assessed for various physicochemical characteristics (Table 1). Properties of soil at experimental locations were examined before beginning of experimentation. For soil EC, 1:5 ratio of soil and water suspension was used [30].

Experimental layout and treatments

Maize was selected based on existing practice and suitability with local agroclimatic situations and economic importance in the mountainous region. During three years (2019, 2020, 2021), research trials were conducted at three locations. At each location, treatments were

Table 2 Thinning treatment details

Thinning treatment	Initial plant density, plants ha-1	Daily thinning, plants ha-1	Plant population at different growth stages, plants ha^{-1}				Total thinning till silking, plants ha^{-1}
			15 DAE (2–5 leaves)	30 DAE (6–7 leaves)	45 DAE (8–9 leaves)	60 DAE (9–10 leaves)	
0%	2×10^5	0	2.00×10^5	2.00×10^5	2.00×10^5	2.00×10^5	0
0.5%	2×10^5	0.01×10^5	1.85×10^5	1.70×10^5	1.55×10^5	1.40×10^5	0.60×10^5
1%	2×10^5	0.02×10^5	1.70×10^5	1.40×10^5	1.10×10^5	0.80×10^5	1.20×10^5
1.5%	2×10^5	0.03×10^5	1.55×10^5	1.05×10^5	0.60×10^5	0.15×10^5	1.85×10^5

Note: DAE_ days after emergence

Table 3 Date wise cultural management activities, sampling of plants and measurement of growth and yield parameters at three experimental locations in three years

No.	Activity	Altitude and cultural practice date of years 2019–2021		
		1500 m	1800 m	2200 m
1	Land ploughing, layout of field, application of basal fertilizer dose and sowing of Maize	June 24th	Jun 28th	Jul 4th
2	Emergence of Maize plants	June 28th	July 3rd	July 10th
3	1st sampling and measurement	July9th	July13th	July 19th
4	2nd sampling and measurement	July 24th	July 28th	August 3rd
5	3rd sampling and measurement	August 8th	August 12th	August 18th
6	4th sampling and measurement	August 23rd	August 27th	September 12th
7	Application of 2nd dose of Nitrogenous fertilizer	September 3rd	September 8th	September 15th
8	5th sampling and measurement	September 8th	September 11th	September 27th
9	Harvesting, sampling and measurement	October 11th	October 23rd	Oct 31st
10	Total cropping days of maize	110	118	120

composed of four daily thinning practices (0, 0.5, 1.0, 1.5%). Thinning treatments were chosen as per practice in the study area where farmers harvest maize for fodder according to the size of domesticated livestock (Personal communication). For a smaller size of livestock (cows, goats etc.) farmers harvest (thinning) a smaller number of plants on daily basis and vice versa. The detail of thinning treatments is presented in Table 2. The treatments were arranged in a factorial arrangement (4×3) adopting the layout of RCBD experimental design at each elevation site. At each trial location (altitude), size of plot was maintained as 4.0 m × 6.0 m. Experimental plots were spaced away by one meter while replicates were distant with vacant area of two-meter. Sowing of maize was done using broadcasting method and initial plant density was arranged as 2×10^5 plants ha^{-1} using seed rate of 20 kg ha^{-1}.

Experimental management

Maize variety Azam was cultivated at designated sites for experimentation following the proper land preparation (Table 3). Irrigation regimes were kept eight to ten and with seven days interval at each site. Synthetic fertilizers namely Urea containing 46% nitrogen, single superphosphate containing 16% P_2O_5 phosphate and potassium chloride containing 60% potassium were applied for normal growth of plants. Recommended levels of potassium and phosphorus at the rate of 30 kg ha^{-1}were used as basal application at the time of seeding. Perhaps, quantity of Nitrogen (113 kg ha^{-1}) was split into two halves where 50% (56.5 kg ha^{-1}) was supplied at the time of sowing while the rest 50% was applied at the booting stage of the crop (Table 2) [31]. Unwanted plants were manually eradicated from the plots during the thinning practices. To control insect pests like shootfly and aphids' pesticides like carbofuran granules (2%) and carbaryl@ 51 kg $ha^{-1}$and 0.27 kg ha^{-1}, respectively, were applied.

Plant parts sampling

For measurement of growth components of maize plants, biweekly plant sampling was carried starting from plant emergence till 75 days. The sampled plants were prepared for measurement of growth components including plant height, number of leaves, leaf area, leaf dry weight, stem dry weight, and plant dry weight. For growth and dry matter computation, five plants were randomly harvested from each replication for biweekly periods of 1 to 15, 16 to 30, 31 to 45, 46 to 60, and 61 to 75 DAE at each experimental location (Table 3). For final yield estimation plants were sampled from experimental plots and biological yield, thousand grain weight and grain yield were computed.

Maize growth and yield assessment

Plant height was computed from ground surface to plant top with the help of measuring tape as described by

Pedersen et al. [32]. Number of leaves of a plant at specified growth stage was counted as elaborated by Perez-Harguindeguy et al. [33]. For leaf area, length and width of a leaf were measured, and product was multiplied with a factor (0.75) as reported by Sun et al. [34]. Stem and leaf dry weights were calculated from sampled plants at all biweekly growth stages and cumulative dry weights of plant components were expressed as total dry weight of a plant as also reported by Koca et al. [35]. Fresh plant parts including leaves and stem were dried in an electric oven at 70 °C till constant weight. Accumulated dry weights of both leaves and stems of five different plants were averaged. Furthermore, absolute growth rate (AGR) was computed from total increase in dry weights of plant and its parts during biweekly growth periods using Eq. 1 and Eq. 2, respectively.

$$Absolute\ growth\ rate,\ g\ plant^{-1}\ day^{-1} = \frac{W_2 - W_1}{t_1 - t_2} \quad (1)$$

Where,

W_1 is plant dry weight at time t_1. W_2 is plant dry weight at time t_2.

Biological yield was computed as reported by others [36]. At full maturity stage of maize, one square meter area was marked in experimental plots using a quadrate. Plants were harvested from land surface within the quadrate. Ears of maize were detached, and remaining parts were oven dried at 70 °C till constant weight. Dry biomass of a plot was converted to biomass production per hectare. Thousand grain weight was calculated as reported by Ramadhan et al. [36]. Ears were removed from harvested plants and threshed and packed in paper bags. Paper bags containing seeds were oven dried till 12% moisture content. One thousand grains were counted and weighed by an electronic balance having accuracy of ± 0.01 g to get thousand grain weight. Maize grain yield was calculated as indicated by Mian et al. [37]. Calculated grain weight was scaled up for a plot first and then extrapolated to hectare. Furthermore, sustainable yield index (SYI) was computed from grain and biological yield of maize as recommended by Sarangi et al. [16] (2020) and Li et al. [17] (2020).

$$\text{Sustainable yield index} = \frac{Average\ yield - Standard\ deviation}{Maximum\ yield} \quad (2)$$

Statistical data analysis

Research data were statistically analyzed using SAS program (Version 9.0) [38] (SAS, 2003). A three-way ANOVA was conducted to determine level of significance for the influence of studied factors (year, altitude & thinning) on growth variables and yield parameters of maize. The Fisher's Protected LSD method was applied to separate means which were significantly varied from each other. Pearson's correlation was computed to know the level of correlation (r) of economic yield and biological yield with growth parameters of maize for different biweekly periods.

Results

Growth variation

A two-way interaction influence of year and altitude was recorded significant ($p \leq 0.05$) and an increase in plant height (PH) was noted during all growth intervals except 61 to 75 DAE (Supplementary Table 1). Increase in growth was the greatest in year 2021 at altitude of 1500 m and was the lowest in year 2019 at altitude 2200 m during all growth intervals (Fig. 2A). In each year, PH was increased however within the altitude it was reduced from the lowest (1500 m) to the highest (2200 m). A two-way interaction of year and thinning treatment was significant ($p \leq 0.05$) for increase in PH during biweekly period of 46–60 and 61–75 DAE (Supplementary Table 1. Biweekly PH increase of maize was maximum for the year 2021 with 0% thinning and the lowest in the year 2019 having 1.5% thinning in all growth periods (Fig. 2B). Furthermore, a two-way interaction effect of altitude and thinning was noted significant ($p \leq 0.05$) on biweekly increase of PH during 46–60 DAE (Supplementary Table 1) where maize with 0% thinning obtained the highest increment of PH at the lowest altitude and less increase in PH was noted at the highest altitude (Fig. 2C). Withing thinning treatments, maize with 0% thinning got the highest increase in PH at low altitudes compared to rest of thinning treatments. Increase in PH was significantly ($p = 0.001$) differed due to individual effect of altitude during 61–75 DAE and due to thinning treatment during 31–45 DAE (Supplementary Table 1). Maize grown at low altitude gained the highest increase in PH compared to that at high altitude during 61–75 DAE (Fig. 2D). Maize with 0% thinning recorded the highest increase in PH compared to 0.5–1.5% daily thinning during 31–45 DAE (Fig. 2E).

The interaction of year and altitude was observed significant ($p \leq 0.05$) for increase in NL during all biweekly growth intervals except from 1 to 75 DAE (Supplementary Table 2). This growth variable was the greatest in the year 2021 at altitude of 1500 m and the lowest in year 2019 at maximum altitude 2200 m during all the biweekly growth intervals (Fig. 3A). Within a year, increment in NL was increased from 2019 to 2021 whereas within the altitude this parameter was reduced from the lowest altitude (1500 m) to the highest altitude (2200 m). Biweekly increase in NL was significantly ($p = 0.001$) different because of the year effect during 61–75 DAE (Fig. 3B), due to altitude during 61–75 DAE (Fig. 3C) and due to thinning during 31–45, 46–60 and 61–75 DAE

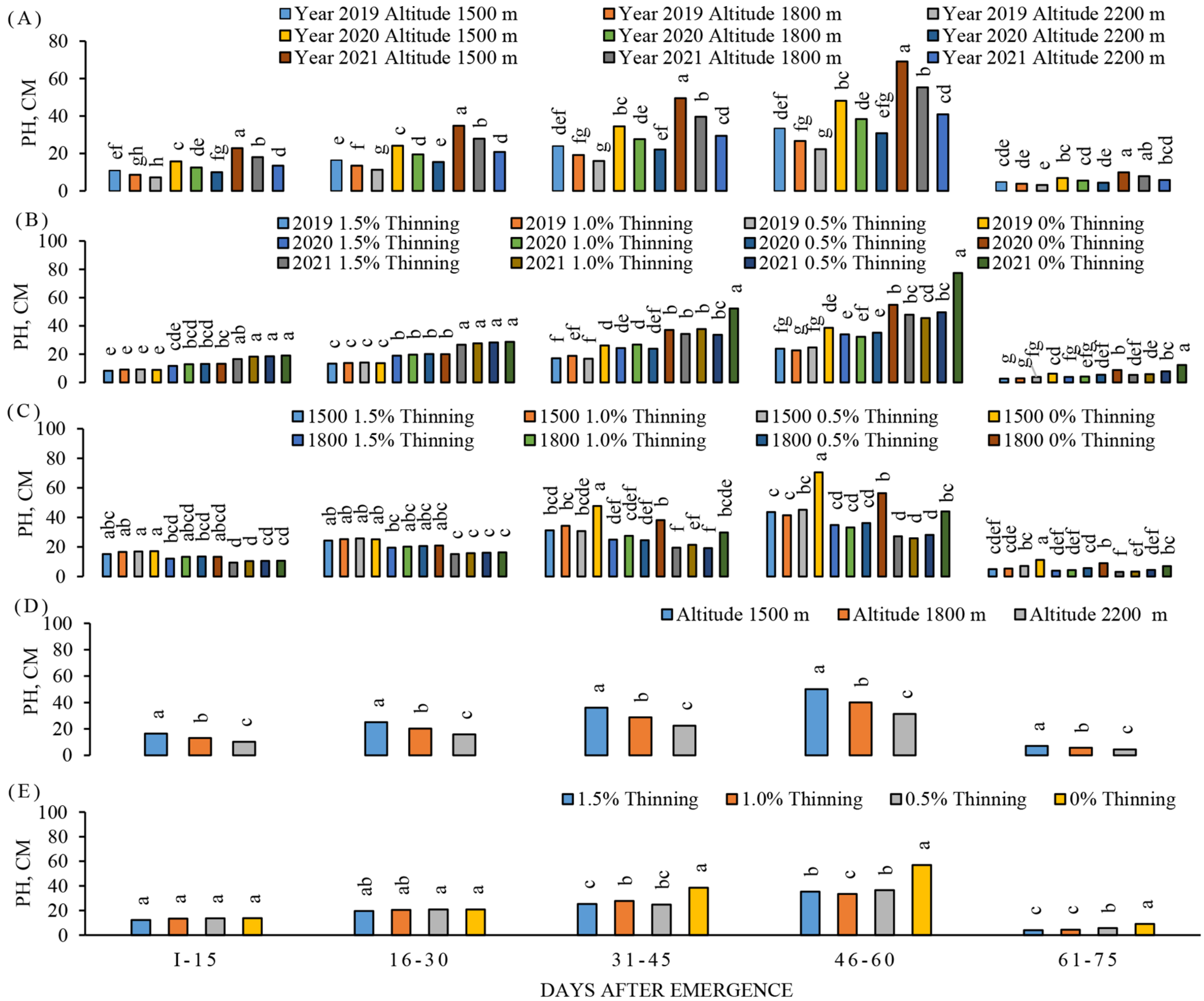

Fig. 2 Interaction effect of year and altitude (**A**), interaction of year and thinning (**B**) and interaction effect of altitude and thinning (**C**) and individual effect of altitude (**D**) and thinning (**E**) on increase in plant height of maize during 1–15, 16–30, 31–45, 46–60, and 61–75 days of emergence of maize (different alphabets show significant difference)

(Fig. 3D). The increase in NL was the greatest during the year 2019 and significantly decreased in 2020 and 2021 in the specified interval. The increase in NL was greater at low altitude and significantly reduced at high altitude. Maize grown without daily thinning got more increase in NL compared to 0.5–1.5% daily thinning during 31–45, 46–60 and 61–75 DAE. Though, among the thinning practices, maize grown with 0.5% thinning produced more increases in NL during all the growth intervals.

A two-way interaction influence of year and altitude was observed significant for LA increase per plant during all growth intervals except 61–75 DAE (Supplementary Table 3). This growth variable was greatest for year 2021 at altitude of 1500 m and was the lowest during the year 2019 at altitude of 2200 m in all growth intervals (Fig. 4A). Within year, the LA was increased from 2019 to 2021, however within altitude, LA was reduced from lowest altitude (1500 m) to the highest altitude (2200 m). The interaction influence of year and thinning was significant ($p \leq 0.05$) for increase in LA from 31 to 45, 46 to 60 and 61 to 75 DAE (Supplementary Table 3). This growth variable was the highest for year 2021 when 1.5% thinning of maize was done, and the lowest value was noted in year 2019 where 0% thinning of maize was carried in all growth intervals except 46 to 75 DAE where 0% thinning of maize obtained the lowest value (Fig. 4B). Increase in LA of maize experienced a significant influence because of altitude during biweekly period of 61–75 DAE. Increase in LA was the highest at 1500 m altitude than that at 1800 and 2200 m altitudes (Fig. 4C).

Dry matter production and distribution

Mean values of biweekly increase in leaf dry weight (LDW) were 11.3, 16.5, 25.6, 17.2, and 9.7 g plant^{-1}.

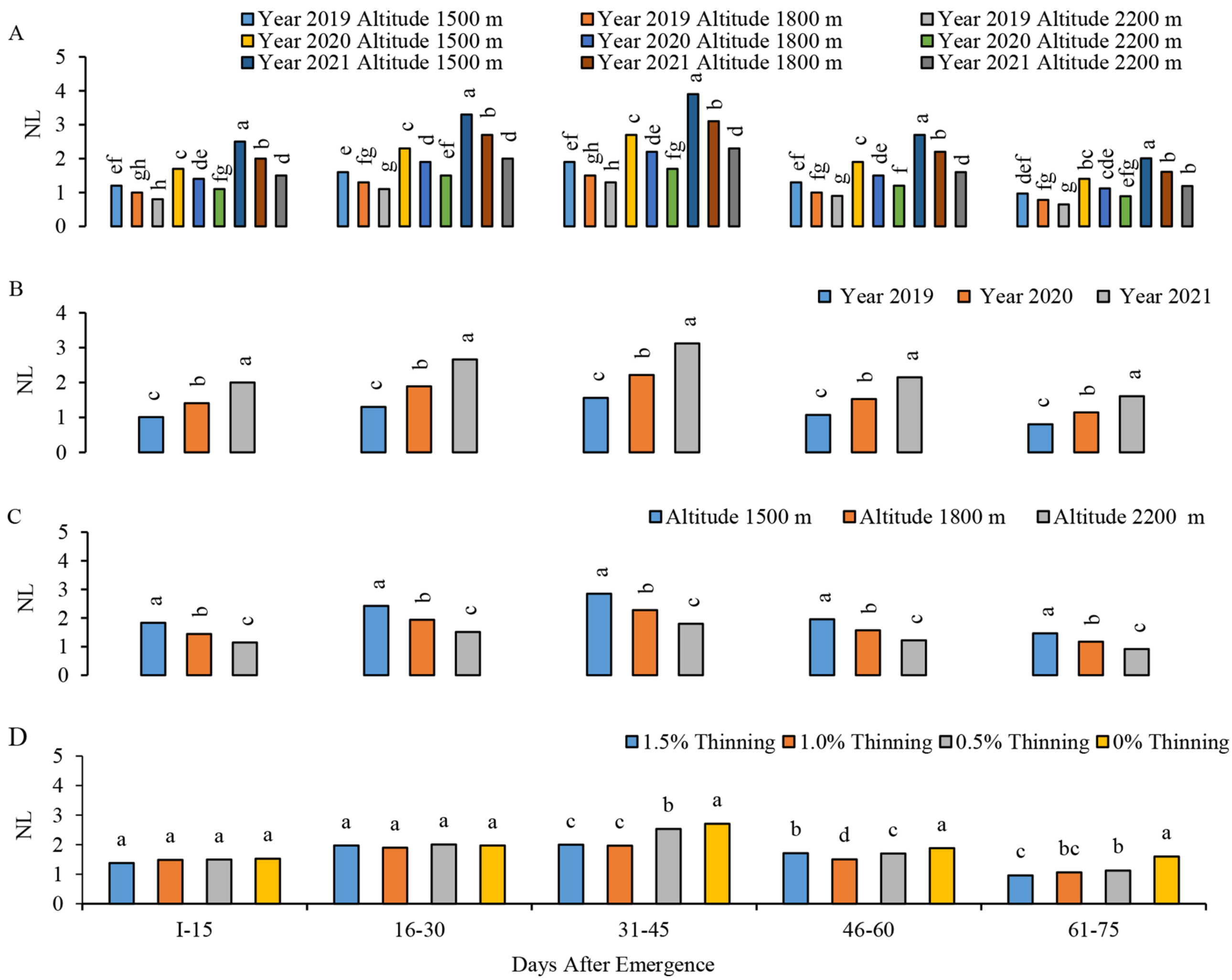

Fig. 3 Interaction effect of year and altitude (**A**) and individual effect of year (**B**), altitude (**C**) and thinning (**D**) on increase in number of leaves per plant during 1–15, 16–30, 31–45, 46–60, and 61–75 days of emergence of maize (different alphabets show significant difference within the growth period)

Similarly, biweekly increase in stem dry weight (SDW) were 18.8, 26.4, 49.9, 35.3, and 8.2 g plant^{-1} and increases in plant dry weight (PDW) were 30.0, 43.8, 75.6, 52.5, and 17.9 g plant^{-1} during 1 to 15, 16 to 30, 31 to 45, 46 to 60, and 61 to 75 DAE, respectively. Biweekly increase in LDW, SDW and PDW among maize stands with and without thinning were significantly ($p = 0.001$) differed because of interaction effect of year and altitude during 1 to 15, 16 to 30, 31 to 45, 46 to 60 and 61 to 75 DAE except biweekly increase in SDW during 31 to 45 and 61 to 75 DAE (Supplementary Tables 4, 5, 6). All dry weights of plant parts in thinned maize were greater in 2021 at 1500 m altitude followed by 2020 at 1800 m altitude and a further biweekly decrease in 2019 at 2200 m altitude (Fig. 5A, B and C). Dry matter assimilation was increased from 2019 to 2021 and from the lowest altitude to the highest altitude and vice versa.

Year and thinning had significant ($p = 0.001$) interaction effect on biweekly increment of LDW during 31 to 45, 46 to 60 and 61 to 75 DAE (Fig. 6A) and on PDW from 31 to 45 and 46 to 60 DAE (Fig. 6B). Highest increase in LDW and SDW of maize were observed where it was raised with 1.5% thinning in 2021 while the lowest values were noted in 2019 where 0% thinning was carried. Among thinned stands, maize grown with 1.5% thinning yielded the greatest dry matter compared to remaining thinned stands of maize. Increase in LDW of maize in 31 to 45 and 46 to 60 DAE were significantly influenced because of interaction between altitude and thinning (Fig. 6C). Increase in SDW of plant was not significantly affected because of any interaction influence but significantly differed owing to individual effect of year (Fig. 7a) and altitude in 31 to 45 and 61 to 75 DAE (Fig. 7D). It was higher in year 2021 and significantly decreased in year 2019 and 2020.

Maize cultivated at 1500 m altitude registered higher increase in SDW compared to that raised at 1800 m and 2200 m altitude. Significant influence of thinning was

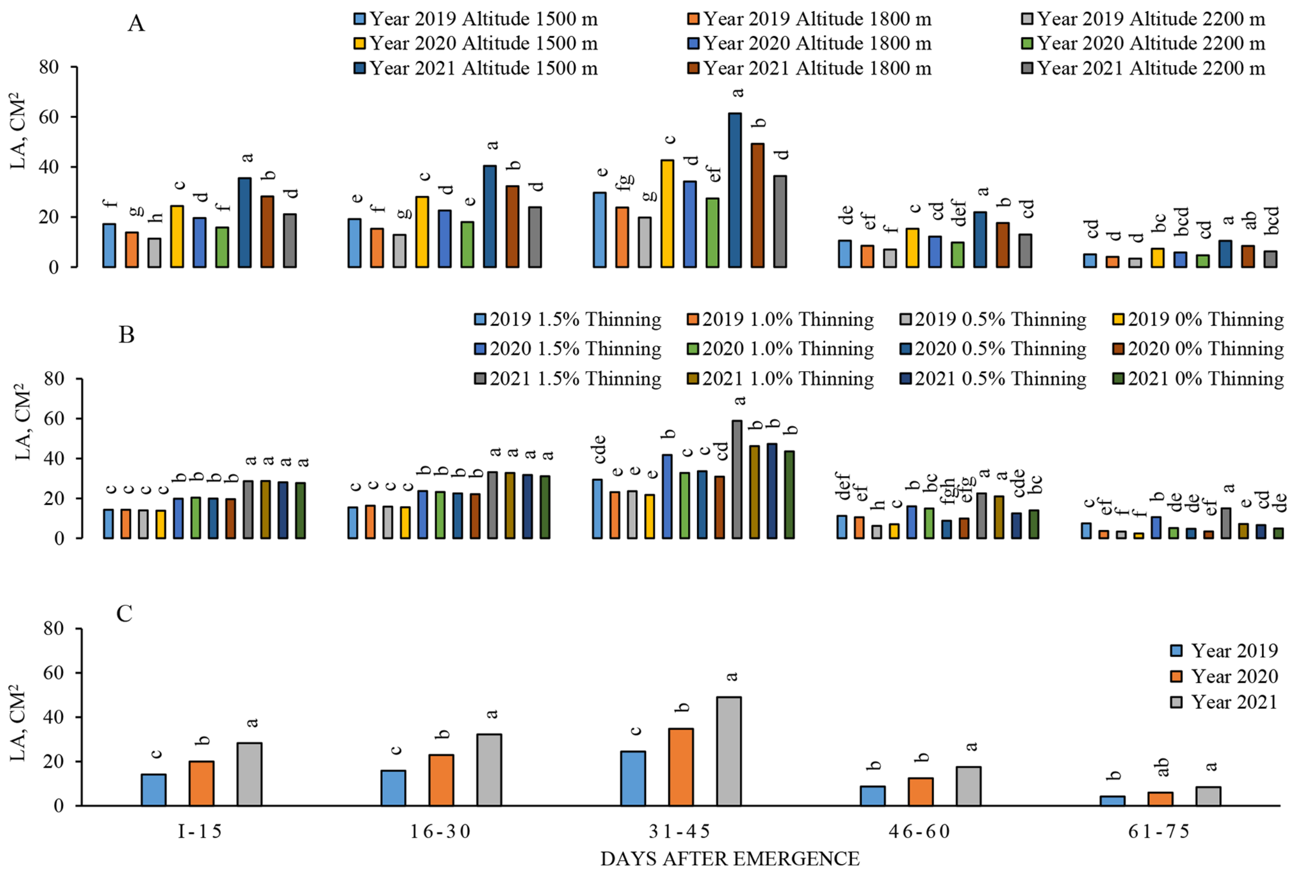

Fig. 4 Interaction effect of year and altitude on incremental leaf area (**A**), interaction effect of year and thinning on incremental leaf area (**B**) and individual effect of year on increase in leaf area (**C**) during 1–15, 16–30, 31–45, 46–60, and 61–75 days of emergence of maize (different alphabets show significant difference)

recorded on biweekly increase in SDW during 31 to 45, 46 to 60 and 61 to 75 DAE periods (Fig. 7C). It was higher in case of 1.5% thinning compared to 0–1% thinning. However, within thinning treatments, increase in SDW was greater where maize was thinned to 1.5% and significantly decreased in other thinning practices. Biweekly increase in PDW significantly ($p = 0.001$) differed owing to thinning in 61 to 75 DAE (Fig. 7D). In this period, maize with 1.5% thinning yielded highest increase in PDW compared to maize with 0–1% daily thinning.

Plant growth of maize with respect to time can also be described in the form of absolute growth rate (AGR) as an indicator of plant growth in a specific period. It is calculated from dry matter yield of plant for a specified time interval. Significant interaction effect of year and altitude and of year and thinning (Supplementary Table 7) was observed for biweekly growth intervals from 1 to 15, 16 to 30, 31 to 45, 46 to 60, and 61 to 75 DAE and of 31 to 45 and 46 to 60 DAE, respectively. Due to these interactions, AGR was increased to a maximum in case of year 2021 and 1500 m altitude (Fig. 8A) and in case of year 2021 and 1.5% thinning in all biweekly periods (Fig. 8B).

Production and yield sustainability

The grain yield (GY), thousand grain weight (TGW) and biological yield (BY) of thinned maize were significantly affected by interaction of year and altitude (Supplementary Table 8). Yield parameters of maize were recorded in year 2021 at 1500 m altitude were the highest and were the lowest in year 2019 at 2200 m altitude (Table 4). Significant influence of thinning was noted on GY, TGW and BY of thinned maize. The TGW of maize significantly higher in case of thinning (0.5–1.5%) and 1.5% thinning of maize yielded highest compared to 0.5-1% thinning (Fig. 9A). The GY and BY of maize were significantly decreased in 1.5% thinning compared to 1% thinning of maize (Fig. 9B and C). Yield sustainability index was computed in range of 0.22 to 0.65 for biological yield and from 0.20 to 0.63 for grain yield (Fig. 9D). Sustainable yield index was greater in case of 1% daily thinning compared to rest of the thinning practices (0%, 0.5%, 1.5%).

Correlation of growth and climate with yield

Relationship of growth parameters and dry matter production with grain and biological yield of maize for the biweekly periods of 1st, 2nd, 3rd, 4^{th,} and 5th is indicated

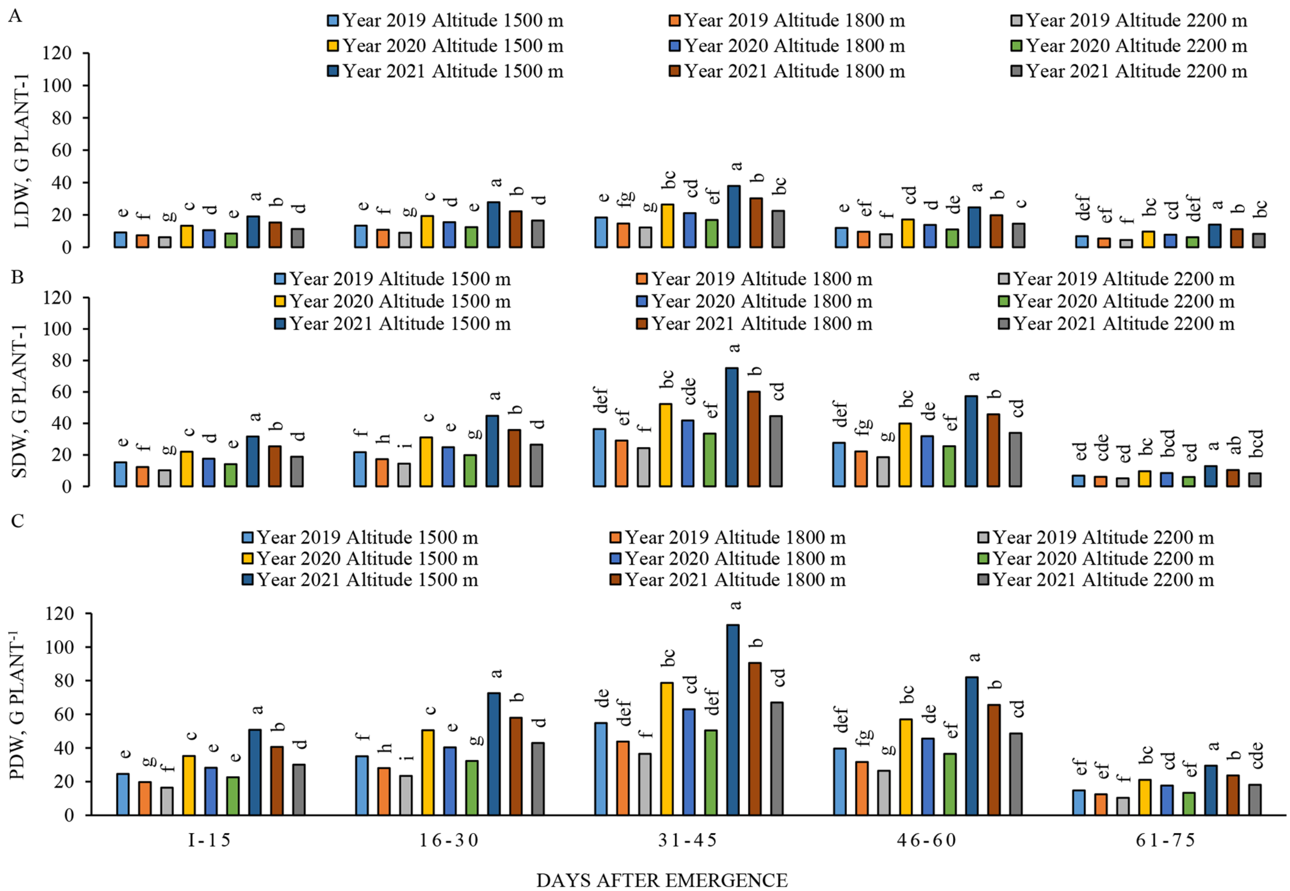

Fig. 5 Interaction influence of year and altitude on increase of leaf dry weight (**A**), stem dry weight (**B**) and plant dry weight (**C**) during 1–15, 16–30, 31–45, 46–60, and 61–75 days of emergence of maize (different alphabets show significant difference)

in Table 5. Maize plant height in the five biweekly periods was significantly ($p=0.001$) associated with both GY and BY of maize where coefficient of correlation (r) ranged from 0.7 to 0.9. Stem diameter found significantly associated with both GY and BY both negatively and positively, respectively. Increase in number of leaves in all biweekly periods significantly linked with GY and BY having the "r" value in the range of 0.8 to 0.9. Biweekly increase in leaf area during 1st, 2nd, 3rd, 4th, and 5th biweekly periods significantly ($p=0.001$) associated with GY and BY having the coefficient of correlation (r) in the range of 0.4–0.9. Increase in dry weight of leaf in 1 to 15, 16 to 30, 31 to 45, 46 to 60 and 61 to 75 DAE significantly ($p=0.001$) associated with economic and biological yield ($r=0.5$–0.9).

Increment in dry weight of stem during 1 to 15, 16 to 30, 31 to 45, 46 to 60 and 61 to 75 DAE significantly ($p=0.001$) linked with the yield ($r=0.4$–0.9). Similarly, dry weight of maize plant also had significant ($p=0.001$) association ($r=0.5$–0.9) with grain and biological yield of maize. The GY and BY were found strongly associated with temperature ($r=0.7$, $r=0.8$) but were not significantly correlated with the pattern of rainfall (Fig. 10A, B, C and D).

Discussion

Decrease in growth and grain yield in case of high-density maize without thinning compared to its thinned counterpart has been indicated in previous research but there is lack of information pertaining to specific periods of differentiation due to different patterns of thinning i.e., 0%, 0.5%, 1% and 1.5% thinning [39]. This research reported growth and time scale rate of growth didn't change during initial growth stages (1–15 DAE and 16–30 DAE) of maize just because of thinning due to less intraspecific competition during these early biweekly periods. With the passage of time, growth per plant and development of maize with 0% thinning was gradually decreased compared to maize with 0.5 to 1.5% thinning. This would be owing to gradual increase in intraspecific competition among the maize plants for both underground and aboveground resources. Till the third biweekly period of growth after emergence, maize plants with 0% and 0.5–1.5% thinning experienced likewise conditions and hence less competition was observed in maize with 1.5%

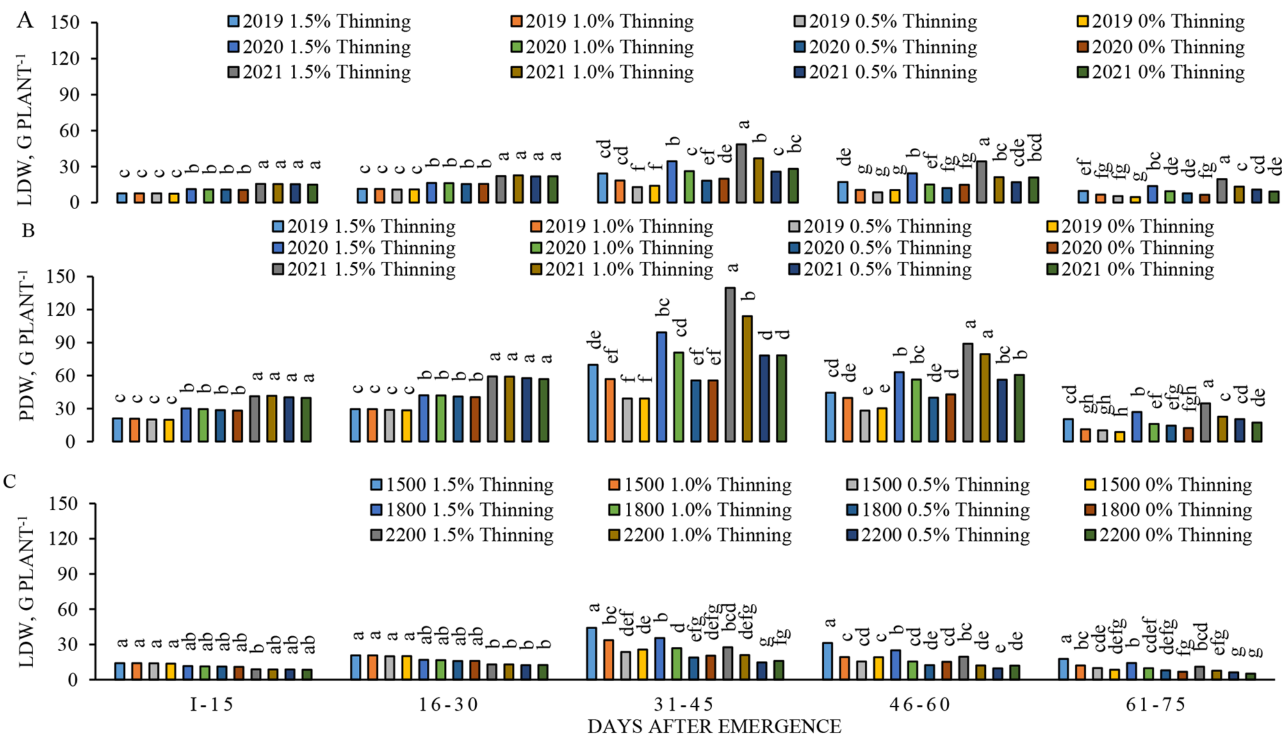

Fig. 6 Interaction influence of year and thinning on leaf dry weight (**A**) and plant dry weight (**B**), and interaction effect of altitude and thinning (**C**) on leaf dry weight of maize after emergence during 1–15, 16–30, 31–45, 46–60, and 61–75 days of emergence of maize (different alphabets show significant difference)

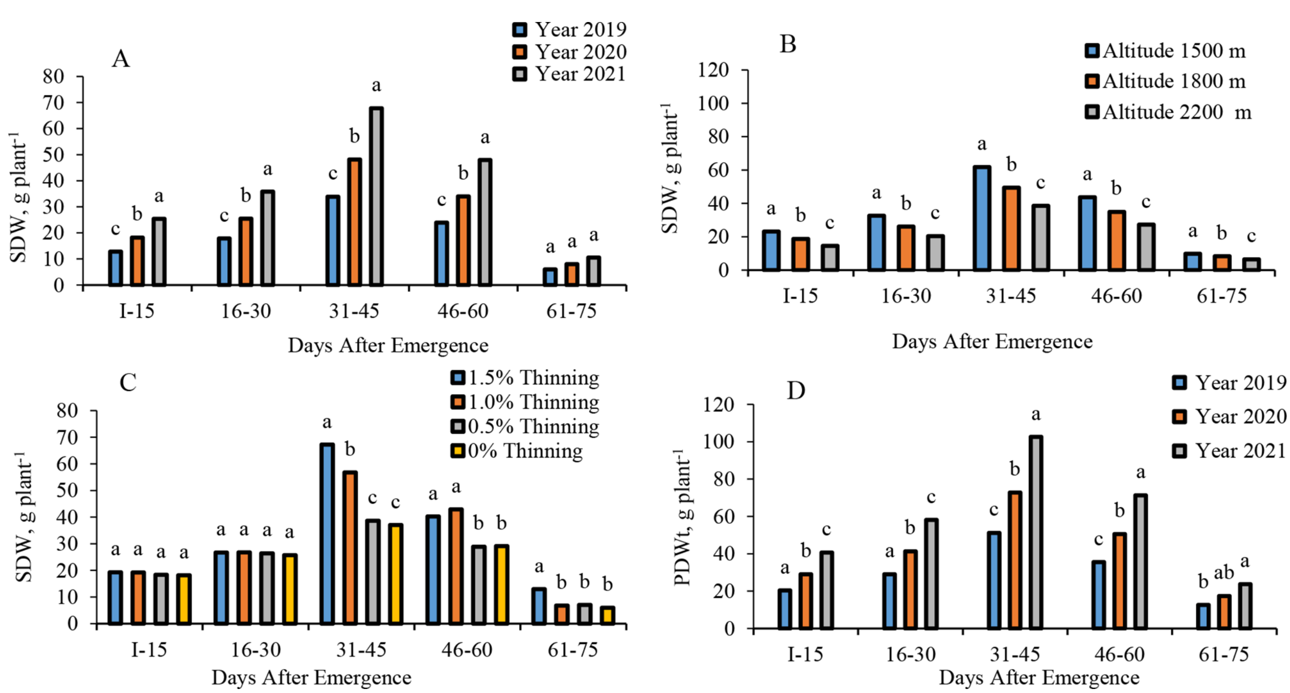

Fig. 7 Influence of year (**A**), altitude (**B**) and thinning (**C**) on increase in stem dry weight and effect of year on increase in plant dry weight (**d**) of maize after emergence (different alphabets indicate significant difference)

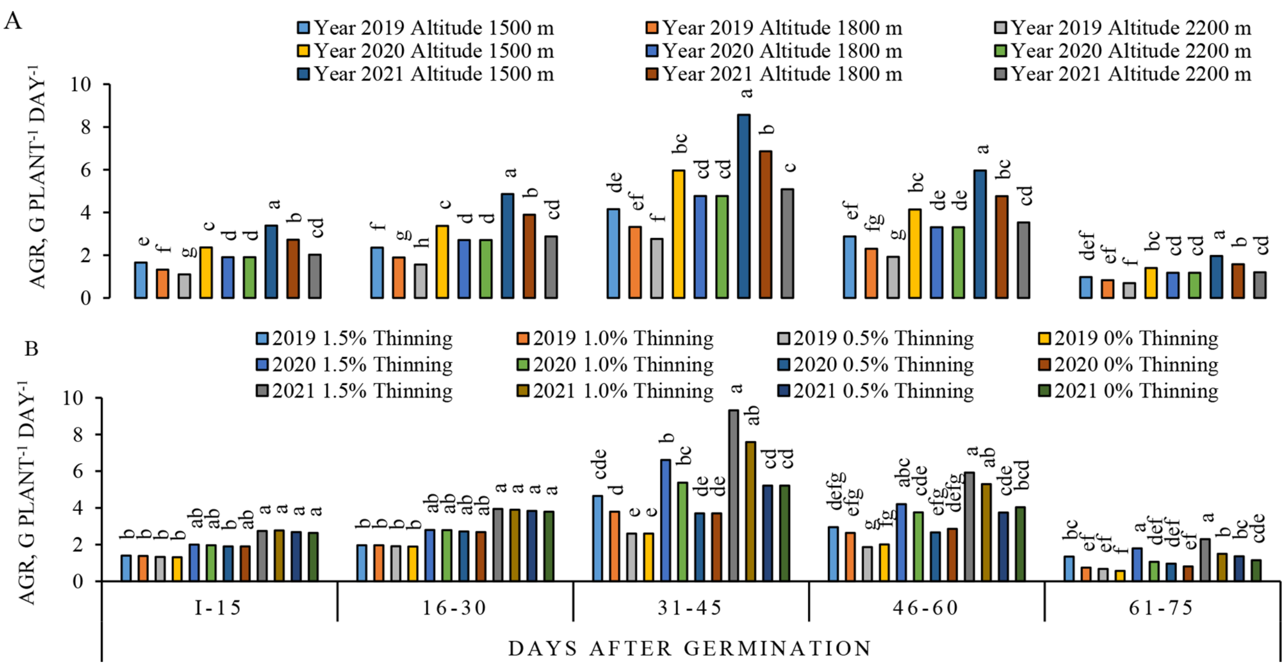

Fig. 8 Interaction influence of year and altitude (**A**) and interaction effect of year and thinning (**B**) on absolute growth rate during 1–15, 16–30, 31–45, 46–60, and 61–75 days of emergence of maize (different alphabets show significant difference)

Table 4 Two-way interaction influence of year and altitude on thousands grain weight, grain yield, and biological yield of maize

Year	Altitude, m	Thousand grain weight, g	Grain yield, t ha^{-1}	Biological yield, t ha^{-1}
2019	1500	80.8 ± 29.9^{ef}	6.9 ± 3.1^{def}	18.0 ± 4.9^{ef}
	1800	64.7 ± 23.9^{gh}	5.5 ± 2.5^{fg}	14.4 ± 4.0^{fg}
	2200	53.9 ± 19.9^{h}	4.6 ± 2.0^{g}	12.0 ± 3.3^{g}
2020	1500	116.2 ± 42.9^{c}	9.9 ± 4.4^{bc}	25.8 ± 7.1^{c}
	1800	93.0 ± 34.4^{de}	7.9 ± 3.5^{cd}	20.7 ± 5.7^{de}
	2200	74.4 ± 27.5^{fg}	6.3 ± 2.8^{de}	16.5 ± 4.5^{f}
2021	1500	167.1 ± 61.7^{a}	14.2 ± 6.3^{a}	37.1 ± 10.2^{a}
	1800	133.7 ± 49.4^{b}	11.4 ± 5.1^{b}	29.7 ± 8.2^{b}
	2200	99.0 ± 36.6^{d}	8.4 ± 3.8^{cd}	22.0 ± 6.1^{d}
$LSD_{0.05}$		15.01	1.83	3.68

Note: DAE_ days after emergence, different superscript alphabets on mean ± SD under each yield parameter indicate significant difference ($LSD_{0.05}$) due to interaction effect of year and altitude

thinning owing to ample resources available for both maize with 0% and 0.5–1.5% thinning due to low plant density. But thereafter, as maize plants development progressed its canopy size increased, competition among the plants started to increase thereby reduced the supply of resources as also noted by Liu et al. [40] in high density scenario of maize.

Development in plant growth can be divided into three phases with respect to plant growth rate and density. In first initial phase plants don't shade each other as they are located sparsely and grow speedily using all available nutrient, water, and light resources. In this period, most of the carbohydrates are used for growth of leaves and enhances leaf area through interception of solar radiation. This speedy growth is due to less effect of mutual shading among maize plants. In second growth phase, plants start to cover land available in vicinity and shade each other.

During this period, high density plant population experienced high competition and a uniform rate of dry matter production was maintained. Even a further increment in leaf area couldn't lead to greater interception of solar radiation because of intensive shading. Therefore, dry matter and absolute growth rate is linearly increased. During the third phase of plant development following the favorable climatic conditions where plants have already explored all the available resources, now crop experienced a significant reduction and subsequently stop of dry matter assimilation due to onset of leaf senescence. Assimilates from leaves and stem are translocated through source sink relationship to form grain yield of a plant [41]. Plant height determines the number of leaves that determines the leaf area of a plant [42]. Greater number of leaves can be seen in plants having higher plant height and more and higher fodder and grain yields can be expected in plant having thicker and long stem. This phenomenon was recorded the strong association of growth and dry matter with maize grain and biological yields in this study.

Daily 1% thinning of maize plants was recorded as advantageous compared to 0, 0.5 and 1.5% thinning. This is because growth, development and dry matter partition were compromised in case of 0, 0.5% and 1.5% daily

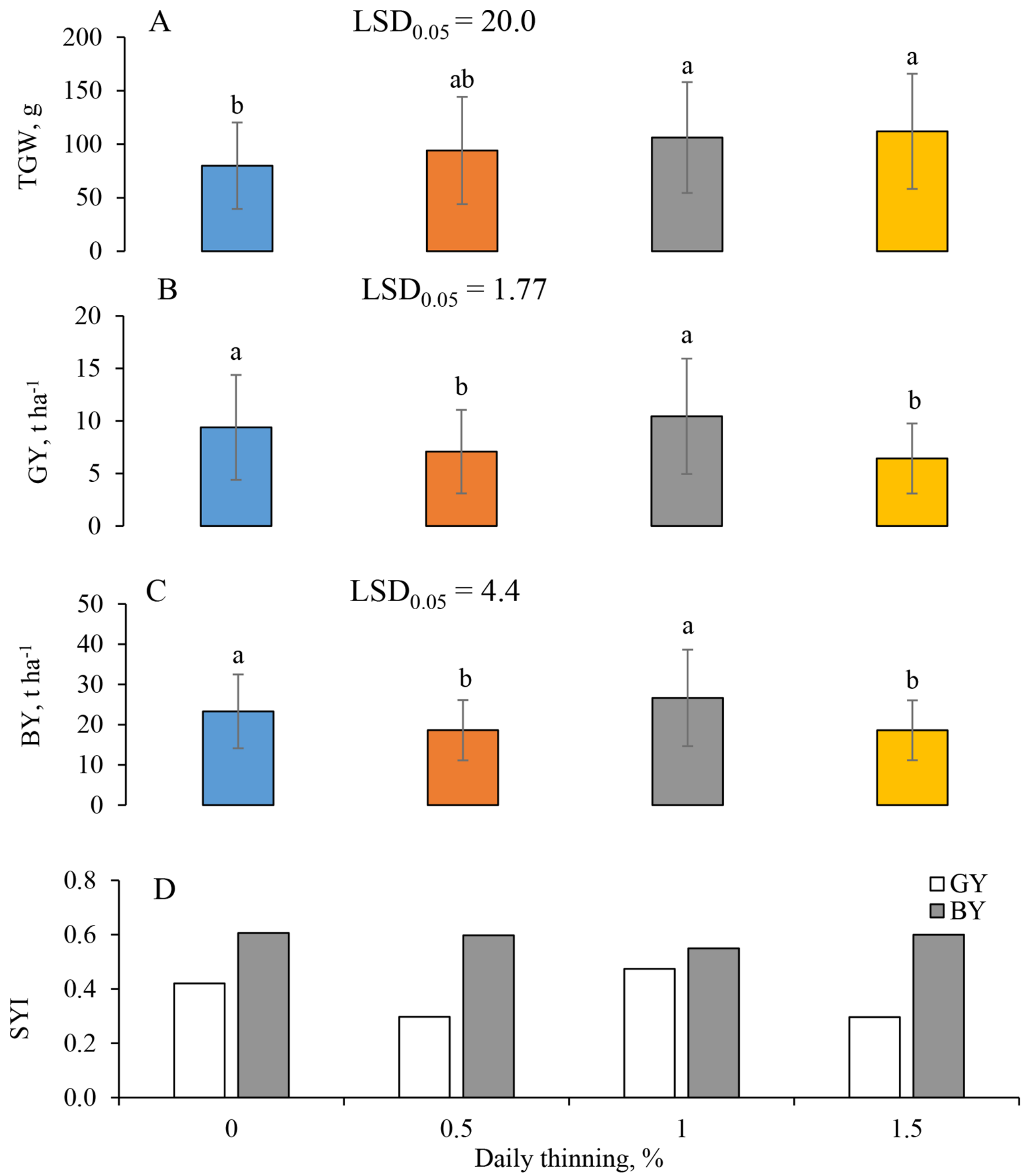

Fig. 9 Effect of thinning on thousand grain weight (TGW) (**A**), grain yield (GY) (**B**), biological yield (BY) (**C**) and sustainable yield index (SYI) (**D**) of maize

thinning. In case of 0% and 0.5% thinning, where maximum density of maize was maintained right from the emergence till harvesting. Hence, a maximum intraspecific competition was experienced by the pants for both below and above ground resources. In case of 0% thinning, where despite of achieving greater plant height, more number of leaves and final plant density, maize plants could not produce the maximum leaf area, dry matter, and final yield due to slim and weak plant structure because of intraspecific competition for the available resources. In case of 1.5% daily thinning, although achieved greater growth and dry matter production per plant it could not produce maximum economic and biological yield per unit area owing to significant loss of plant population due to intensive daily thinning practices. Due to 1.5% daily thinning, more than 50% plants were removed and finally harvested plants per unit area were notably less compared to 1% thinning plot. Therefore, among the thinning patterns, higher grain and biomass yields of maize and their sustainable yield indices were noticed due to better performance of crop in 1% thinning practice where optimum plant density was maintained

Table 5 Correlation of growth and biological yield with growth variables for 1 to 15, 16 to 30, 31 to 45, 46 to 60, and 61 to 75 days after emergence (DAE) of maize

Harvest	Growth parameter	Days after germination					
		1–15 DAE	**16–30 DAE**	**31–45 DAE**	**46–60 DAE**	**61–75 DAE**	**Total**
Grain yield	Plant height	0.91***	0.90***	0.81***	0.82***	0.75***	0.88***
	Stem diameter	-0.43***	-0.76***	0.48***	-0.70***	-0.75***	-0.43***
	No. of leave	0.90***	0.82***	0.82***	0.89***	0.83***	0.90***
	Leaf area	0.82***	0.85***	0.66***	0.70***	0.38***	0.72***
	Leaf dry weight	0.88***	0.90***	0.60***	0.57***	0.49***	0.76***
	Stem dry weight	0.89***	0.83***	0.57***	0.67***	0.40***	0.61***
	Plant dry weight	0.89***	0.87***	0.59***	0.66***	0.46***	0.48***
Biological yield	Plant height	0.83***	0.90***	0.88***	0.81***	0.68***	0.85***
	Stem diameter	0.09ns	-0.70***	0.57***	-0.65***	-0.68***	-0.30***
	No. of leave	0.85***	0.89***	0.81***	0.87***	0.77***	0.89***
	Leaf area	0.89***	0.90***	0.76***	0.71***	0.40***	0.80***
	Leaf dry weight	0.89***	0.90***	0.65***	0.63***	0.56***	0.81***
	Stem dry weight	0.90***	0.89***	0.60***	0.73***	0.43***	0.73***
	Plant dry weight	0.89***	0.90***	0.63***	0.73***	0.52***	0.75***

Note: *** indicates highly significantly correlated

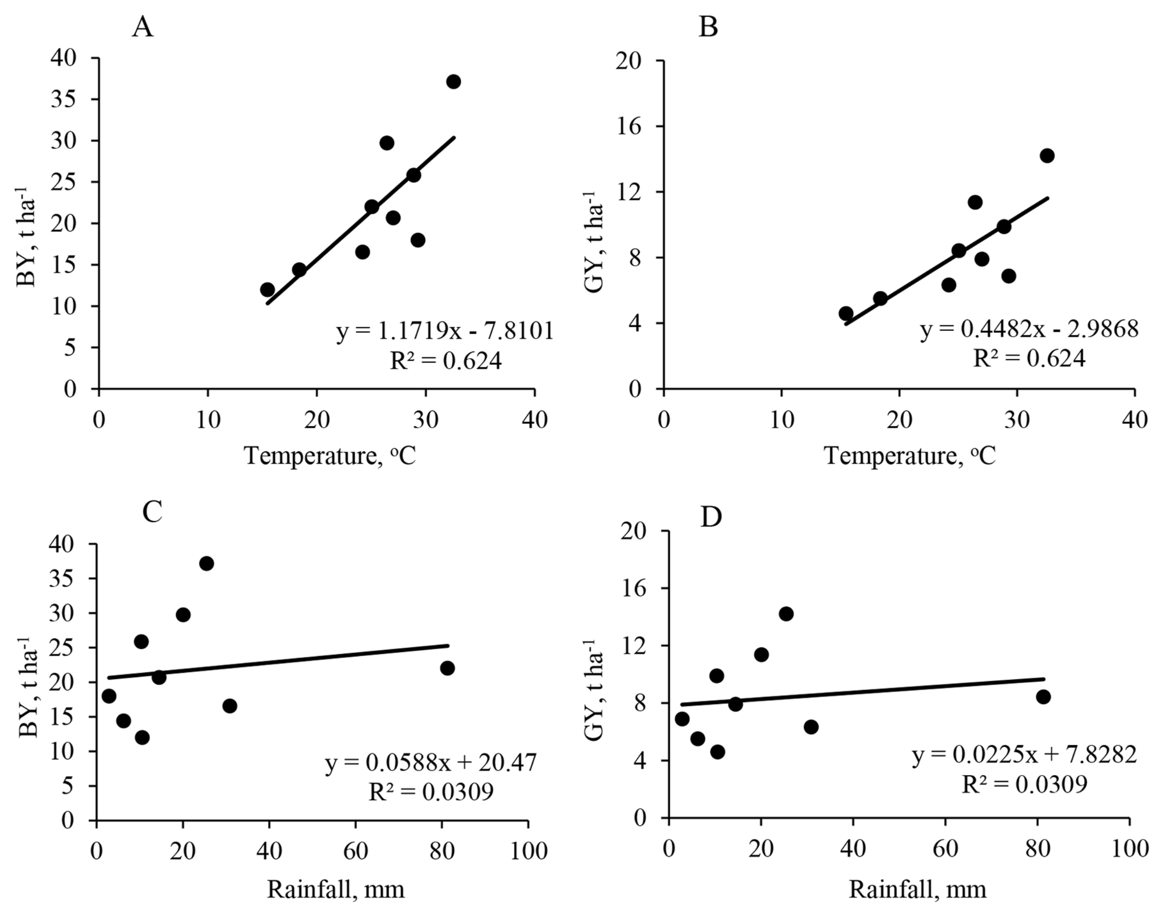

Fig. 10 Relationship of biological (BY) and grain yields (GY) of maize with average temperature (**A**, **B**) and rainfall (**C**, **D**) of study sites during experimental period

compared to its performance under 0.5% and 1.5% thinning patterns including 0% daily thinning of maize.

Conclusions

Current study reported that 1st and 2nd biweekly periods are competition free while 3rd, 4th and 5th biweekly periods are important with respect to intraspecific competition. Further, this research highlighted 1% daily thinning is optimum to ameliorate intraspecific competition for maximum biological and economic harvests from high density broadcasted maize in mountain agroecosystem. Strong correlation of growth variables with biological and economic yields of maize can be used as good predictor of final yields of maize. Broadcasting high density maize with 1% daily thinning at low altitudes is suggested in temperate agroclimatic conditions to achieve higher and sustainable harvests for food security and fodder availability in mountain agroecosystem. Cultivated area to be sown and volume of fodder to be harvested according to the size of livestock being reared are the future directions for this line of research.

Abbreviations

AGR	Absolute growth rate
BY	Biological yield
DAE	Days after emergence
GY	Grain yield
LA	Leaf area
LDW	Leaf dry weight
NL	Number of leaves
PDW	Plant dry weight
PH	Plant height
SDW	Stem dry weight
SYI	Sustainable yield index
TGW	Thousand grain weight

Supplementary Information

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Supplementary Material 1

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Author contributions

Conceptualization, original draft writing, reviewing, and editing: M.A., R.N., S.A., M.A.I. Formal analysis, investigations, funding acquisition, reviewing, and editing: A.I., M.M.N.Q., K.S.A., M.A. Resources, data validation, data curation, and supervision: Z.A., M.B., K.S.A.

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Data availability

All data generated or analysed during this study are included in this published article.

Declarations

Ethics approval and consent to participate

No ethics approval is needed from the authority in Pakistan to collect Maize plants for research purposes. However, land owner approved the collection of the Maize plant for research purposes. All stakeholders have consented to participate.

Consent for publication

All authors consented to publish this research work.

Arrive guidelines

The experimentation was conducted in accordance with applicable laws, and ARRIVE guidelines.

IUCN policy statement

The collection of plant material complies with relevant institutional, national, and international guidelines and legislation.

Competing interests

The authors declare no competing interests.

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References

1. Zhang G, Shen D, Ming B, Xie R, Hou P, Xue J, Wang K, Li S. Optimizing planting density to increase maize yield and water use efficiency and economic return in the arid region of Northwest China. Agriculture. 2022;12:1322. https://doi.org/10.3390/agriculture12091322.
2. Djaman K, Allen S, Djaman DS, Koudahe K, Irmak S, Puppala N, Darapuneni MK, Angadi SV. Planting date and plant density effects on maize growth, yield and water use efficiency. Environ Challenges. 2022;6:100417. https://doi.org/10.1016/j.envc.2021.100417.
3. Tareen WH. Farming system in the marginalized mountainous region of district Battagram in Khyber Pakhtunkhwa. Pakistan J Agricultural Res. 2017;53:12–20.
4. Ali H, Shafi MM, Khan H, Haidar H. Nexus between off-farm employment and farm size among small farm holders in Peshawar Valley of Khyber Pakhtunkhwa. Sarhad J Agric. 2019;35:874–9. https://doi.org/10.17582/journal.sja/2019/35.3.874.879.
5. Shaikh S, Tunio S. 2013. Pakistan's mountain farmers 'helpless' in face of erratic weather: Issues & Analysis. Thomson Reuters Foundation, Trust. Org (TRF). Retrieved from https://www.preventionweb.net/news/view/35392
6. Rasul G, Saboor A, Tiwari PC, Hussain A, Ghosh N, Chettri GB. Food and nutrition security in the Hindu Kush Himalaya: unique challenges and niche opportunities. In: Wester P, Mishra A, Mukherji A, Shrestha AB, editors. The Hindu Kush himalaya assessment: mountains, climate change, sustainability, and people. Cham: Springer; 2019. pp. 301–38.
7. Sekaran U, Lai L, Ussiri DAN, Kumar S, Clay S. Role of integrated crop-livestock systems in improving agriculture production and addressing food security– A review. J Agric Food Res. 2021;5:100190. https://doi.org/10.1016/j.jafr.2021.100190.
8. Abdelaal HAS, Thilmany D. Grains production prospects and long run food security in Egypt. Sustainability. 2019;11:4457. https://doi.org/10.3390/su11164457.
9. Arshad M, Saif-Ud-Din, Ahmed S, Nafees MA, Sharista, Karim A, Ullah S. Response of maize varieties to different nitrogen levels under agro-climatic condition of Gilgit-Baltistan. Pure Appl Biology. 2020;9(2):1541–6. https://doi.org/10.19045/bspab.2020.90161.
10. Arshad M. Fortnightly dynamics and relationship of growth, dry matter partition and productivity of maize based sole and intercropping systems at different elevations. Eur J Agron. 2021;130:126377. https://doi.org/10.1016/j.eja.2021.126377.
11. Kumar N, Satpal, Kumar S, Devi U, Utaliya JM, Shweta. Maize fodder production under changing Climatic scenario for nutritional security of livestock– a review. Forage Res. 46(1):10–21. https://www.researchgate.net/publication/344433163
12. Parent B, Leclere M, Lacube S, Semenov MA, Welcker C, Martre P, Tardieu F. Maize yields over Europe May increase in spite of climate change, with an

appropriate use of the genetic variability of flowering time. Proc Natl Acad Sci USA. 2018;115:10642–7. https://doi.org/10.1073/pnas.1720716115.
13. Song L, Jin J, He J. Effects of severe water stress on maize growth processes in the field. Sustainability. 2019;11:5086. https://doi.org/10.3390/su11185086.
14. Liebig T, Ribeyre F, Laderach P, Poehling H, van Asten P, Avelino J. Interactive effects of altitude, microclimate, and shading system on coffee leaf rust. J Plant Interact. 2019;14:407–15. https://doi.org/10.1080/17429145.2019.1643934.
15. Stein M, Miguez F, Edwards J. Effects of plant density on plant growth before and after recurrent selection in maize. Crop Sci. 2016;56:2882–94. https://doi.org/10.2135/cropsci2015.09.0599.
16. Sarangi D, Jena D, Santra GH, Choudhury S. Sustainable yield index (SYI) of a groundnut-maize cropping system as influenced by sources and management of phosphorus on the acid Alfisols. J Pharmacognosy Phytochemistry. 2020;9:1732–6. https://api.semanticscholar.org/CorpusID:221780850.
17. Li M, Zhang K, Eldoma IM, Fang Y, Zhang F. Plastic film mulching sustains high maize (*Zea Mays* l.) grain yield and maintains soil water balance in semiarid environment. Agronomy. 2020;10:600. https://doi.org/10.3390/agronomy10040600.
18. Huang Z, Liu Q, An B, Wu X, Sun L, Wu P, Liu B, Ma X. Effects of planting density on morphological and photosynthetic characteristics of leaves in different positions on Cunninghamia lanceolata saplings. Forests. 2021;12:853. https://doi.org/10.3390/f12070853.
19. Simin T, Davie-Martin CL, Petersen J, Hoye TT, Rinnan R. Impacts of elevation on plant traits and volatile organic compound emissions in deciduous tundra shrubs. Sci Total Environ. 2022;837:155783. https://doi.org/10.1016/j.scitotenv.2022.155783.
20. Parveen S, Rudra SG, Singh B, Anand A. Impact of high night temperature on yield and pasting properties of flour in early and late-maturing wheat genotypes. Plants. 2022;11:3096. https://doi.org/10.3390/plants11223096.
21. Wittemann M, Andersson MX, Ntirugulirwa B, Tarvainen L, Wallin G, Uddling J. Temperature acclimation of net photosynthesis and its underlying component processes in four tropical tree species. Tree Physiol. 2022;42:1188–202. https://doi.org/10.1093/treephys/tpac002.
22. Raza G, Mirza SNM, Akbar M, Ali M, Hussian F, Hussian A, Ali S, Hussian J. Variation in productivity along the altitudinal gradients in central Karakorum National park (CKNP), Pakistan. Pak J Bot. 2022;54:2273–9. https://doi.org/10.30848/PJB2022-6(25).
23. Li YC, Dai HY, Chen H. Effects of plant density on the aboveground dry matter and radiation-use efficiency of field corn. PLoS ONE. 2022;17:e0277547. https://doi.org/10.1371/journal.pone.0277547.
24. Gao Y, Liang Y, Fu Y, Si Z, Hamani AKM. Interactive effects of intraspecific competition and drought on stomatal conductance and hormone concentrations in different tomato genotypes. Horticulturae. 2022;8:45. https://doi.org/10.3390/horticulturae8010045.
25. Sherin G, Aswathi KPR, Puthur JT. Photosynthetic functions in plants subjected to stresses are positively influenced by priming. Plant Stress. 2022;4:100079. https://doi.org/10.1016/j.stress.2022.100079.
26. Jalal A, Oliveira CED, Galindo FS, Rosa PAL, Gato IMB, de Lima BH, Teixeira Filho MCM. 2023. Regulatory mechanisms of plant growth-promoting rhizobacteria and plant nutrition against abiotic stresses in Brassicaceae family. Life 13, 211. https://doi.org/10.3390/life13010211 Feng, L.Y., Raza, M.A., Chen, Y., Khalid, M.H.B., Meraj, T.A., Ahsan, F., Fan, Y., Du, J., Wu, X., Song, C., Liu, C., Bawa, G., Zhang, Z., Yuan, S., Yang, F., Yang, W., 2019.
27. Feng L, Raza MA, Chen Y, Khalid MH, Meraj TA, Ahsan F, Fan Y, Du J, Wu X, Song C, Liu C, Bawa G, Zhang Z, Yuan S, Yang F, Yang W. Narrow-wide row planting pattern improves the light environment and seed yields of intercrop species in relay intercropping system. PLoS ONE. 2019;14(2):e0212885.
28. Lynch JP, Doyle D, McAuley S, McHardy F, Danneels Q, Black LC, White EM, Spink J. The impact of variation in grain number and individual grain weight on winter wheat yield in the high yield potential environment of Ireland. Eur J Agron. 2017;87:40–9. https://doi.org/10.1016/j.eja.2017.05.001.
29. Zishiri RM, Mutengwa CS, Tandzi LN, Manyevere A. Growth response and dry matter partitioning of quality protein maize (*Zea Mays* l.) genotypes under aluminum toxicity. Agronomy. 2022;12:1262. https://doi.org/10.3390/agronomy12061262.
30. FAO. Standard operating procedure for soil electrical conductivity, soil/water. 2015;1:5. Rome.
31. Arshad M. Effect of Intercropping, Elevation and Nitrogen Dose on Performance of Maize-mungbean Cropping Systems. Proceedings of the Pakistan Academy of Sciences: Pakistan Academy of Sciences B. Life and Environmental Sciences. 2017;353–364. http://www.paspk.org/wp-content/uploads/2018/01/Effect-of-Intercropping.pdf
32. Pedersen IF, Christensen JT, Sorensen P, Christensen BT, Rubæk GH. Early plant height: A defining factor for yields of silage maize with contrasting phosphorus supply. Soil Use Manag. 2021;38:37–548. https://doi.org/10.1111/sum.12697.
33. Perez-Harguindeguy N, Diaz S, Garnier E, Lavorel S, Poorter H, Jaureguiberry P, Bret-Harte MS, Cornwell WK, Craine JM, Gurvich DE, Urcelay C, Veneklaas EJ, Reich PB, Poorter L, Wright IJ, Ray P, Enrico L, Pausas JG, de Vos AC, Cornelissen JHC. New handbook for standardized measurement of plant functional traits worldwide. Aust J Bot. 2013;61:167–234. https://doi.org/10.1071/BT12225.
34. Sun J, Gao J, Wang Z, Hu S, Zhang F, Bao H, Fan Y. Maize canopy photosynthetic efficiency, plant growth, and yield responses to tillage depth. Agronomy. 2019;9:3. https://doi.org/10.3390/agronomy9010003.
35. Koca YO, Erekul O. Changes of dry matter, biomass, and relative growth rate with different phenological stages of corn. Agric Agric Sci Proc. 2016;10:67–75. https://doi.org/10.1016/j.aaspro.2016.09.015.
36. Ramadhan MN. Yield and yield components of maize and soil physical properties as affected by tillage practices and organic mulching. Saudi J Biol Sci. 2021;28:7152–9. https://doi.org/10.1016/j.sjbs.2021.08.005.
37. Mian MAK, Kakon SS, Zannat ST, Begum AA. Plant population is the function of grain yield of maize. Open J Plant Sci. 2021;6:103–7. https://doi.org/10.17352/ojps.000042.
38. SAS. Statistical analysis system. SAS release 9.0 for windows. Cary, NC, USA: SAS Institute Inc. 2003.
39. Shah AN, Mohsin T, Asad A, Mehmet Y, Ali SA, Irfan AM, Zhiwei W, Weiwei S, Youhong S. Combating dual challenges in maize under high planting density: stem lodging and kernel abortion. Front Plant Sci. 2021;12:699085. https://doi.org/10.3389/fpls.2021.699085.
40. Liu G, Yang Y, Liu W, Guo X, Xie R, Ming B, Xue J, Zhang G, Li R, Wang K, Hou P, Li S. Optimized canopy structure improves maize grain yield and resource use efficiency. Food Energy Secur. 2022;11:e375. https://doi.org/10.1002/fes3.375.
41. Lemoine R, La Camera S, Atanassova R, Dedaldechamp F, Allario T, Pourtau N. Source-to-sink transport of sugar and regulation by environmental factors. Front Plant Sci. 2013;4:272. https://doi.org/10.3389/fpls.2013.00272.
42. Ammanullah, Shah P, Marwat KB. Nitrogen levels and its time of application influence leaf area, height and biomass of maize planted at low and high density. Pak J Bot. 2009;41:761–8. https://api.semanticscholar.org/CorpusID:82195616.

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