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Research Article

Evaluating the Effect of Cultivar and Planting Dates on Garlic Growth and Yield in North Dakota

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Abstract

Planting date and cultivar selection are critical factors influencing garlic growth and yield. This study was conducted at two locations to evaluate the effects of three planting dates (Sept 28, Oct 12, Oct 25) and six cultivars ('German White' (GW), 'Music' (Mus), 'Georgia Fire' (GF), 'Korean Mountain' (KM), 'Georgia Crystal' (GC), and 'German Extra Hardy' (GEH)) on garlic growth and yield. Data were collected on leaf number (LN), plant height (PH), scape length (SL), scape weight (SW), bulb weight (BW), bulb diameter (BD), plant fresh weight (PFW), plant dry weight (PDW), and clove number (CN). Results showed that the interaction between cultivar and planting date significantly influenced PH, LN, PFW, PDW, SL, and BD but not SW, CN, or BW. The cultivar 'GW' planted on Oct 12 had the most leaves, whereas 'GEH' planted on Oct 25 had the fewest leaves. The tallest plants were 'GW' planted Oct 12 and 'Mus' planted Sept 28, while 'GEH' had the shortest plants when planted Oct 25. The greatest PFW was 'GW' planted on Sept. 28, while 'GEH' planted on Oct 25 had the lowest PFW, approximately 87% lower than the highest. Similarly, the highest PDW was 'GW' planted Sept 28, whereas 'GEH' planted on Oct 25 had the lowest PDW, approximately 84% less than 'GW' planted Sept 28. The longest scapes were 'Mus' planted Sept 28 and 'GW' planted Oct 12. The BD for 'GW' planted Sept 28 were 99% larger compared to 'GEH' planted Oct 25, which had the smallest BD. The cultivar and location interaction also significantly affected LN, PH, PFW, PDW, SW, SL, but not BD, BW or CN. The highest leaf number were 'GW' and 'Mus' planted at the Horticulture Research Farm (HRF), while the tallest plants, longest scapes, and heaviest scapes were 'GW' planted at the HRF. The greatest PFW were 'GW' planted at the HRF, while 'KM' at the HRF had the lowest PFW, which was 71% lower. Similarly, 'GW' planted at the HRF had the greatest PDW, whereas 'KM' planted at the HRF had the lowest, approximately 64% lower PDW. The interaction between location and planting date significantly influenced PH, LN, PDW, SL, SW, BD and BW but not PFW or CN. The highest PDW, SW, and SL were garlic planted Sept 28 at the HRF, while the lowest values were garlic planted Oct 25 at the Agriculture Experiment Station (AES) plot in Fargo. The most leaves produced, and tallest plants were when garlic were planted Sept 28 at the HRF, while the fewest leaves and shortest plants were garlic planted Oct 25 at the HRF. The greatest BD and BW was when garlic were planted Sept 28 at the HRF, which was 263% higher than the lowest BW and 57% larger than the smallest BD of garlic planted Oct 25 at the HRF. The correlation analysis revealed strong positive relationships between BW and PFW, PDW, BD, and SW, indicating that these traits were strong selection criteria for improving garlic bulb yield while LN, CN, and SL exhibited moderate to low correlations with BW. Results indicate that 'GW' was the most adaptable cultivar under North Dakota conditions and that early fall planting, particularly around Sept 28, significantly enhanced garlic yield, making it a recommended practice for optimizing production.

Introduction

Garlic *(Allium sativum)*, a member of the Amaryllidaceae family, is a widely consumed allium crop, second only to onions, and is native to Central Asia [1,2]. It is primarily used as a spice and condiment but is also recognized for its therapeutic properties, including antiviral, antibacterial, antifungal, immune-boosting, anti-diabetic, hepatoprotective, anti-fibrinolytic, and antioxidant effects [3,4]. These health benefits are largely attributed to the sulfur-containing compound allicin, which has driven increased consumption and demand for garlic [5]. However, despite its nutritional and economic significance, garlic production remains low in the US due to the lack of improved cultivars [6].

Cultivar selection significantly influences garlic traits such as bulb size, clove number, and yield [6-9]. Akbarpour et al. [10] demonstrated that different garlic ecotypes exhibit variability in yield, phytochemical composition, and leaf production. Specific cultivars also had superior growth and yield due to their vegetative capacity [11]. Environmental factors, including temperature and photoperiod, play crucial roles in garlic growth, phytohormone activity, and allicin production [12-16]. High temperatures (30°C) and extended day lengths (14 hours) promote vegetative growth and bulb development, with temperature and photoperiod also affecting cultivar adaptability to specific regions [17-22]. Planting date is another critical factor influencing garlic productivity. Early fall planting maximizes exposure to optimal environmental conditions, leading to larger bulbs and higher yields, while delayed planting negatively affects productivity [23-25]. Fall planting has been shown to produce higher yields than spring planting, despite the risk of winter damage [26-28]. Vernalization, coupled with longer day lengths, enhances garlic growth, bulb quality, and yield [16,29].

Therefore, optimal planting time, cultivar selection, and environmental factors, including temperature and photoperiod, are key determinants of garlic growth and yield. Research on these variables is essential for improving garlic production, particularly in regions like North Dakota (ND), where planting time and cultivar characteristics can serve as selection tools for high-yielding cultivars. The research objective was to determine the effects of the planting date and cultivar on garlic growth and yield in ND and to determine certain garlic traits that can serve as a selection tool in determining high yielding garlics.

Materials and Methods

Experimental Site

Trials were conducted at the North Dakota State University (NDSU) Horticulture research farm (HRF) near Absaraka, ND (97º 21' W & 46º 59' 28N) and the NDSU main agricultural experiment station (AES) in Fargo, ND Fargo (96º 48' 49" W & 46º 53' 33"N). The soil at the HRF is a sandy clay loam with a pH of 7.1 and 7.0 at a depth of 15 and 30cm, respectively and 1.7% organic matter at a depth of 30 cm. The soil characteristics at the AES is a silty clay with a pH of 8.0 at both 15 and 30cm depth with 5.1% and 4.8% organic matter at 15 and 30 cm depth, respectively (NDSU Soil test report,2024). Climatic conditions for both locations were recorded from nearby weather stations [30] (Table 1).

Table 1: Rainfall, soil and air temperature, and solar radiation across for each garlic experiment location in North Dakota.

	Agriculture Experiment Station, Fargo				Horticulture Research Farm, Absaraka			
Month	2023-2024				2023-2024			
	Ave. air temp. ºC	Ave. bare soil temp. ºC	Ave. solar radiation KJ/m²	Total rainfall mm	Ave. air temp. ºC	Ave. bare soil temp. ºC	Ave. Solar Radiation KJ/m²	Total Rainfall mm
Sept	18.3	18.9	14,058	51.6	17.8	17.8	13179.6	46.7
Oct	8.33	10.6	9246	47.5	7.78	10.6	8995.6	29.7
Nov	0.00	2.22	5857	4.57	-0.56	2.22	5732.08	3.56
Dec	-1.11	0.00	3515	77.7	-2.78	0.00	3598.24	48.0
Jan	-9.44	-2.78	4979	4.32	-10.56	-1.11	5271.84	3.05
Feb	-1.67	-0.56	8661	18.8	-1.67	-0.56	8451.68	17.8
Mar	-1.11	0.00	12552	10.7	-1.67	0.00	13179.6	6.35
Apr	7.78	6.11	15272	66.0	7.22	5.56	15982.88	84.1
May	13.9	13.9	19205	149	13.3	12.8	19622.96	129
Jun	18.9	20.0	22301	114	17.8	18.3	23095.68	80.5
Jul	22.8	23.9	22133	45.2	21.7	21.7	23304.88	29.0
Aug	20.6	21.7	16778	66.5	19.4	19.4	18242.24	78.7

$Avg. (Average), Temp. (Temperature), Rad (Radiation)

Experimental Procedure

Six of the highest performing cultivars from previously conducted cultivar trials were used in a one-year study conducted at the HRF and AES locations to examine the effects of planting dates and cultivars on garlic growth and yield in North Dakota. Six garlic cultivars 'German White' (GW), 'Music' (Mus), 'Georgia Fire' (GF), 'Korean Mountain' (KM), 'Georgia Crystal' (GC), and 'German Extra Hardy' (GEH) and three planting dates (September 28, October 12, and October 25) were arranged as a two factor randomized complete block design with four replications. Five cloves were planted for each cultivar within an experimental unit. Each experimental unit was approximately 38.1 cm long and 25.4 cm wide with 10.2 cm between experimental units and 61 cm between double rows. Field cultivation occurred just prior to planting with a tractor and disk and any uprooted weeds were removed to provide soil tilth suitable for garlic growth. The first of a three-way split application of 20-20-20 fertilizer (at 26.9 kg N/ha) was incorporated after initial tillage. Five cloves were then planted for each cultivar within an experimental unit at 5 to 10 cm depth and 10 by 10 cm spacing in a zig-zag staggered pattern. The soil holes were created with a planting dibble (Johnny's Selected Seed, Winslow, ME). Split and smaller cloves were discarded to provide consistency within trials. Following the first killing freeze (≤ 0 °C), wheat *(Triticum aestivum)* straw was applied to a 5-8 cm depth as a protective mulch. Drip irrigation was installed after snow melt during the spring to supply water for the garlic growth. After snow melt, the second split of fertilizer was incorporated and one month later the final fertilizer application occurred. When the first sign of garlic emergence occurred, rows were watered weekly with 25 mm of water.

Plants were harvested when one-third to one-half of the plant's leaves turned brown or yellow [31]. Garlic grown at the AES were harvested July 24,2024 whereas garlic grown at the HRF were harvested July 25, 2024. Garlic harvest was completed with the help of a garden fork to reduce stem and bulb injury.

Data Collection

Garlic leaf number (LN) and plant height (PH) were measured and recorded 30, 45, 60, and 80 days after emergence (DAE) in the spring. Scape length (SL) at 50% scape emergence and scape weight (SW) after removal were measured and recorded. Harvested garlic plants were brought to the lab (protected from direct sunlight) immediately after uprooting to measure and record plant fresh weight (PFW). Plants were then stored in perforated bags to cure for approximately three weeks in a well-ventilated room with a relative humidity of 60-70% [31]. After curing, the plant dry weight (PDW) was measured and recorded. Garlic stems were then cut approximately 2.5 cm above the main bulb and the roots were trimmed close to the base of the bulb before data such as clove number (CN), bulb weight (BW), and bulb diameter (BD) were measured and recorded.

Statistical Analysis

In order to have the valid statistical analysis, a residual normality plot of histogram from PROC UNIVARIATE of SAS (Statistical Analysis Systems, Cary, NC) was primarily used to check the distribution of residuals normality test for each response random variable that is approximately bell-shaped, and symmetrical, indicating that the assumption of normality test of residual for each of response random variable for the ANOVA and regression model of general linear model is likely followed a normal distribution. Once the assumptions of normality of residuals of each response variable followed a normal distribution, then the analysis of variance using PROC GLIMMIX data=; model yi =factors / dist=options; Lsmeans factors /lines Ilink along with adjust=Bonferroni's adjustment was used for experiment-wise or comparison-wise of Lsmeans comparisons among measured parameters. PROC CORR was used for correlation analysis to measure either a positive or a negative association, with a value between 1 or -1. To visualize correlation between two traits, "PROC SGPLOT" was used to create scatter plots, enabling calculation of confidence intervals into the scatter plots.

Results

Plant growth parameters

The three-way interaction of cultivar, planting date, and location were significant for plant growth parameters: LN, PH, PFW, PDW, and SW and yield parameters: BD and BW. Only growth parameter SL (P = 0.1502) and yield parameter CN (P = 0.1953) did not have significant three-way interactions. Similarly, the two-way interactions of cultivar by planting date, cultivar by location, and location by planting date were significant for all plant growth and yield parameters with the except of SW, CN, and BW for the cultivar by planting date interaction, PFW and CN for the location by planting date interaction, and BD, BW, and CN for the cultivar by location interaction. In addition, garlic location by DAE interaction were not significant for plant height (P = 0.5381) and garlic cultivar by DAE interaction were not significant for leaf number (P = 1.0000). Finally, the planting date and DAE interaction were not significant for leaf number (P = 0.9728).

Garlic location and DAE influenced leaf number (P < 0.0001). The highest leaf number (7.72) was recorded 80 DAE for plants grown at the AES (Table 2). The lowest leaf number (5.29) was recorded 30 DAE for plants grown at the AES. The location and DAE interaction occurred because the increase in plant leaf number over time was greater when plants were grown at the AES than at the HRF.

Table 2: Effect of location and days after emergence on garlic leaf number when averaged over six cultivars and three planting dates in North Dakota.

Location	Time (DAE)	Leaf number
		Mean ± SE
HRF[b]	30	5.61 ± 0.14 e[a]
	45	6.89 ± 0.14 c
	60	7.06 ± 0.14 bc
	80	7.11 ± 0.14 bc
AES	30	5.29 ± 0.13 f
	45	6.48 ± 0.13 d
	60	7.32 ± 0.13 b
	80	7.72 ± 0.13 a
P-value	<.0001	

[a]Garlic leaf numbers with the same letter in a column are not significantly different from each other based on Lsmeans at P ≤ 0.05.
[b]Abbreviations: HRF = Horticulture Research Farm near Absaraka, ND, AES = Agriculture Experiment Station in Fargo, ND

Garlic cultivar and DAE influenced plant height, (P = 0.0055). The tallest plants (82.8 cm) were 'GW' at 80 DAE, while the shortest plants (33.0 cm) were 'GC' at 30 DAE (Table 3). However, the short 'GC' at 30 DAE were not significantly different from 'GC', 'GF', 'GEH', or 'KM' at 30 DAE. The garlic cultivar and DAE interaction occurred because all four short cultivars had similar heights up to 60 DAE, but from 60 to 80 DAE, 'GC' and 'KM' only grew approximately 1 cm while 'GF' and 'GEH' grew approximately 3cm and 4cm, respectively.

Table 3: Effect of cultivar and days after emergence on plant height when averaged over locations in North Dakota and planting dates.

Cultivar	Time (DAE)	Plant height Mean ± SE -----cm-----
GC[b]	30	33.0 ± 1.75 h[a]
	45	50.0 ± 1.75 f
	60	63.2 ± 1.75 de
	80	63.8 ± 1.75 c-e
GF	30	34.5 ± 1.70 h
	45	52.3 ± 1.70 f
	60	65.5 ± 1.70 cd
	80	68.3 ± 1.70 c
GEH	30	33.3 ± 2.13 h
	45	48.0 ± 2.13 f
	60	60.7 ± 2.13 de
	80	65.0 ± 2.13 c-e
GW	30	39.6 ± 1.82 g
	45	62.7 ± 1.82 de
	60	81.7 ± 1.82 a
	80	82.8 ± 1.82 a
KM	30	33.8 ± 1.82 h
	45	48.8 ± 1.82 f
	60	61.5 ± 1.83 de
	80	62.0 ± 1.83 de
Mus	30	39.9 ± 1.70 g
	45	60.5 ± 1.70 e
	60	76.2 ± 1.70 b
	80	78.5 ± 1.70 ab
P-value		0.0055

[a]Garlic heights with the same letter in the column are not significantly different from each other using Lsmeans at P ≤ 0.05.
[b]Abbreviations: GC = Georgia Crystal, GF = Georgia Fire, GEH = German Extra Hardy, GW = German White, KM = Koran Mountain, and Mus = Music.

Planting date and DAE influenced plant height (P = 0.0018). The tallest plants (83.1 cm) were planted on Sept 28 at 80 DAE, while the shortest plants (25.7 cm) were planted on Oct 25 at 30 DAE (Table 4). The planting date by DAE interaction occurred because plants from the first planting date only increased in height by 89% by 80 DAE while plants from the last planting date increased their height by 109% by 80 DAE.

Table 4: Effect of planting date and days after emergence on plant height averaged over cultivars and locations in North Dakota.

Planting date	Time (DAE)	Plant height
		Mean ± SE
		----cm------
Sept 28	30	43.9 ± 1.19 f[a]
	45	65.0 ± 1.19 c
	60	80.8 ± 1.19 a
	80	83.1 ± 1.19 a
Oct 12	30	37.6 ± 1.19 g
	45	56.6 ± 1.19 d
	60	71.1 ± 1.19 b
	80	73.7 ± 1.19 b
Oct 25	30	25.7 ± 1.47 h
	45	39.6 ± 1.47 g
	60	52.3 ± 1.47 e
	80	53.6 ± 1.47 de
P-value		0.0018

[a]Garlic height with the same letter in the column are not significantly different from each other based on Lsmeans at $P \leq 0.05$.

Both leaf number and plant height generally decreased with delayed planting across all cultivars (Table 5). The highest leaf number was recorded with 'GW' (7.9) planted Oct 12, the second planting date. This cultivar was the source of the interaction as 'GW' was the only cultivar with an increase in leaf number on the second planting date. Cultivars 'GF', 'KM', and 'Mus' planted Sept 28 had similar leaf numbers as 'GW' planted Oct 12. The lowest leaf number was recorded with 'GEH' planted Oct 25, the last planting date. This cultivar had almost a 50% decrease in leaf number when compared to the first planting date and fewer leaves than any other cultivar and planting date combination. The interaction occurred because 'GW' leaf number increased when planted Oct 12 compared to Sept 28 while 'Mus', 'KM' and 'GF' leaf number decreased gradually from early to late planting date.

The tallest plants were 'GW' (72.1 cm) planted Oct 12 and 'Mus' (72.1 cm) planted Sept 28 (Table 5). Cultivars 'GF', 'GEH' and 'GW' planted Sept 28 were also considered the tallest plants. On the other hand, the shortest plants were 'GEH' (27.9 cm) planted Oct 25, which was shorter than all other cultivars and planting date combinations. The interaction mimicked that of the leaf number the only difference is that 'GEH', and 'GC' were not stable but decrease gradually from early to mid PD.

Table 5: Effect of garlic cultivar and planting date on leaf number and plant height averaged over two locations (Horticulture Research Farm and Agriculture Extension Station) in North Dakota.

Cultivar	Planting date	Leaf number	Plant height
		Mean ± SE	Mean ± SE
			-------cm-----
GC[b]	Sept 28	7.03 ± 0.17 d-g[a]	62.0 ± 1.5 de†
	Oct 12	6.91 ± 0.17 e-g	56.1 ± 1.5 fg
	Oct 25	5.22 ± 0.18 j	39.4 ± 1.6 hi
GF	Sept 28	7.88 ± 0.17 a	68.3 ± 2.7 a-c
	Oct 12	6.97 ± 0.17 e-g	55.6 ± 1.5 fg
	Oct 25	5.88 ± 0.17 i	41.7 ± 1.5 h
GEH	Sept 28	7.16 ± 0.17 c-e	69.9 ± 1.5 ab
	Oct 12	7.06 ± 0.17 d-f	57.4 ± 1.5 f
	Oct 25	3.68 ± 0.26 k	27.9 ± 2.4 j
GW	Sept 28	7.41 ± 0.17 b-d	69.9 ± 1.5 ab
	Oct 12	7.91 ± 0.17 a	72.1 ± 1.5 a
	Oct 25	6.65 ± 0.20 f-h	58.2 ± 1.8 ef
KM	Sept 28	7.56 ± 0.17 a-c	67.1 ± 1.5 bc
	Oct 12	6.44 ± 0.17 h	51.8 ± 1.5 g
	Oct 25	5.12 ± 0.20 j	35.6 ± 1.8 i
Mus	Sept 28	7.66 ± 0.17 ab	72.1 ± 1.5 a
	Oct 12	7.22 ± 0.17 c-e	64.8 ± 1.5 cd
	Oct 25	6.63 ± 0.17 gh	54.4 ± 1.5 fg
P-value		<.0001	<.0001

[a]Means in a column with the same letter are not significantly different based on Lsmeans at $P \leq 0.05$.
[b]Abbreviations: GC = Georgia Crystal, GF = Georgia Fire, GEH = German Extra Hardy, GW = German White, KM = Koran Mountain, and Mus = Music.

The highest PFW was 'GW' (139 g) planted Sept 28, which was heavier than any other cultivar and planting date combination except 'GW' planted Oct 12 (Table 6). In contrast, GEH' planted Oct 25 had the lowest PFW (18.7 g), approximately 87% lower than 'GW' planted Sept 28. The large decrease in PFW for 'GEH' from the first planting date (112 g) to the last planting date (18.7 g) was responsible for the interaction as several other cultivars had lower PFW with the first planting date and higher PFW with the last planting date.

The greatest PDW was 'GW' (74.4 g) planted Sept 28 which highlighted this treatment's superior growth under early fall planting conditions (Table 6). In contrast, the lowest PDW was 'GEH' (11.8 g) planted Oct 25, approximately 84% lower than 'GW' planted Sept 28. Like PFW, the large decrease in PDW for 'GEH' from the first planting date (62.4 g) to the last planting date (11.8 g) was responsible for the interaction as several other cultivars had lower PDW with the first planting date and higher PDW with the last planting date.

The longest SL was 'Mus' and 'GW' (55.4 cm) when planted Sept 28 and Oct 12, respectively, although the longest SL was not significantly different from 'GF','GEH','GW', and 'KM' planted on Sept 28 and 'Mus' planted on Oct 12 (Table 6). On the other hand, the shortest SL was 'Mus' (13.6 cm) planted Oct 25. The interaction occurred because SL was almost the same for 'GC' planted from Sept 28 to Oct 12 and then sharply decreased when planted Oct 25. 'German White' had slightly longer SL when planted Oct 12 compared to Sept 28 and slightly decreased shorter SL when planted Oct 25. In contrast, plant SL gradually decreased with delayed planting dates for the rest of the cultivars.

The interaction between cultivar and planting date was not significant for SW (p=0.1226). The SW averaged over all cultivars was the greatest when garlic was planted Sept 28 (9.7 g) and the least when garlic was planted Oct 25 (3.9 g). The SW averaged over all planting dates was the greatest for 'GW' (10.9 g), which was greater than the SW for any other cultivar. The lowest SW occurred with all the other cultivars except 'Mus'.

Table 6: Effect of garlic cultivar and planting date on plant fresh weight, plant dry weight, and scape length averaged over two locations (Horticulture Research Farm and Agriculture Extension Station) in North Dakota.

	Cultivars					
	GCb	GF	GEH	GW	KM	Mus
	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
PFW[b]	---------- g ----------					
Sept 28	68.8 ± 4.71 c-e[a]	82.4 ± 8.56 cd	112 ± 7.56 b	139 ± 13.60 a	64.2 ± 4.47 d-f	113 ± 9.51 b
Oct 12	46.1 ± 3.59 f-h	58.6 ± 6.27 e-g	55.6 ± 8.84 e-h	125 ± 6.64 ab	41.6 ± 16.69 hi	84.4 ± 9.04 c
Oct 25	25.4 ± 3.48 i	27.0 ± 4.43 i	18.7 ± 5.38 i	63.1 ± 8.93 e-h	20.8 ± 1.56 i	40.3 ± 7.09 g-i
P-value	---------- 0.0017 ----------					
PDW	---------- g ----------					
Sept 28	41.7 ± 3.30 cd	44.8 ± 3.67 cd	62.4 ± 4.30 b	74.4 ± 8.16 a	38.5 ± 2.32c-e	57.1 ± 2.93 b
Oct 12	28.0 ± 2.17 fg	31.7 ± 3.17 ef	31.3 ± 4.69 ef	61.8 ± 3.10 b	22.2 ±5.55 gh	45.0 ± 4.07 c
Oct 25	15.2 ± 2.18 h	14.1 ± 1.89 h	11.8 ± 2.34 h	37.8 ± 5.13 d-f	12.9 ± 0.79 h	21.2 ± 3.21 gh
P-value	---------- 0.0011 ----------					
SL						
Sept 28	45.2 ± 4.3 b-e	50.3 ± 6.2 a-c	54.1 ± 5.0 a	52.6 ± 6.7 ab	54.9 ± 4.9 a	55.4 ± 5.4 a
Oct 12	42.7 ± 3.3 c-e	40.1 ± 4.7 ef	42.4 ± 3.6 c-f	55.4 ± 5.3 a	40.6 ± 3.1 d-f	48.8 ± 4.0 a-d
Oct 25	24.9 ± 3.7 gh	33.3 ± 4.2 fg	25.3 ± 5.2 h	49.5 ± 3.5 ab	26.7 ± 2.2 gh	13.6 ± 1.6 fg
P-value	---------- 0.0011 ----------					

[a]Means with the same letter for each growth parameter are not significantly different using LSMeans at P ≤ 0.05.
[b]Abbreviations: PFW = plant fresh weight, PDW = plant dry weight, SL = scape length, and SW = scape weight, GC = Georgia Crystal, GF = Georgia Fire, GEH = German Extra Hardy, GW = German White, KM = Koran Mountain, and Mus = Music.

Leaf production was the greatest when ‘GW’ and ‘Mus’ were planted at either location and ‘GF’ was planted at the HRF with approximately seven leaves (Table 7). The lowest leaf number was when ‘GEH’ was planted at the HRF (5.5 leaves). The cultivar by location interaction occurred because ‘GEH’ had a 15% increase in leaf number when planted at the AES compared to the HRF while ‘KM’ and ‘GC’ had approximately a 2% decrease when planted at the AES compared to the HRF.

The tallest plant was ‘GW’ planted at the HRF (68.8 cm) while the shortest plants were ‘GC’ planted at the AES (49.5 cm), although they were not significantly different from ‘GEH’, and ’KM’ planted at the HRF or ‘GF’ and ‘KM’ planted at the AES (Table 7). The cultivar by location interaction occurred because the plant height decreased for ‘GF’, ‘GC’, and ‘KM’ when planted at the AES while ‘GEH’ plant height increased when planted at the AES. Similarly, 'GW’ plant height decreased when planted at the AES while ‘Mus’ plant height increased when planted at the AES.

Table 7: Effect of cultivar and location on leaf number and plant height averaged over planting dates for garlic grown in North Dakota.

Location	Cultivar	Leaf number	Plant height
		Mean ± SE	Mean ± SE
			-------cm-------
HRF[b]	GC[b]	6.46 ± 0.15 bc[a]	55.4 ± 1.27 cd
	GF	7.08 ± 0.15 a	58.4 ± 1.19 c
	GEH	5.55 ± 0.19 d	49.8 ± 1.70 ef
	GW	7.35 ± 0.16 a	68.8 ± 1.40 a
	KM	6.43 ± 0.16 bc	52.3 ± 1.40 d-f
	Mus	7.15 ± 0.15 a	63.2 ± 1.19 b
AES	GC	6.31 ± 0.15 c	49.5 ± 1.19 f
	GF	6.73 ± 0.15 b	52.1 ± 1.19 ef
	GEH	6.38 ± 0.15 c	53.6 ± 1.27 de
	GW	7.29 ± 0.15 a	64.5 ± 1.19 b
	KM	6.31 ± 0.15c	50.8 ± 1.19 ef
	Mus	7.19 ± 0.15 a	64.3 ± 1.19 b
P-value		0.0012	0.0003

[a]Means with the same letter in a column are not significantly different based on Lsmeans at $P \leq 0.05$.
[b]Abbreviations: AES = Agriculture Experiment Station in Fargo, ND, HRF = Horticulture Research Farm near Absaraka, ND, GC = Georgia Crystal, GF = Georgia Fire, GEH = German Extra Hardy, GW = German White, KM = Koran Mountain, and Mus = Music.

The cultivar 'GW' planted at either the HRF or the AES had the highest PFW of 111 g and 103 g, respectively and was greater than any other cultivar and location combination (Table 8). On the other hand, 'KM' grown at the HRF had the lowest PFW (32.1 g), approximately 71% less than 'GW' grown at the same location. The cultivar by location interaction occurred because 'KM', 'GC' and 'Mus' had increased PFW when grown at the AES compared to the HRF while other cultivars remained relatively stable for both locations.

The 'GW' cultivar planted at either the HRF or the AES had the greatest PDW of 60.1 g and 53.8 g, respectively and was greater than any other cultivar and location combination (Table 8). The lowest PDW was when 'KM' was planted at the HRF (21.6 g), which was 64% less than the PDW for 'GW' planted at the same location. However, the low PDW for 'KM' planted at the HRF did not differ from the PDW for 'GC','GF' and 'KM' grown at the AES. The cultivar by location interaction occurred because 'GC' had a slightly lower PDW at the AES location compared to the HRF location, while the PDW for 'KM' had a greater PDW at the AES location compared to the HRF location.

'German White' planted at the HRF had the highest SW (15.4 g), which was greater than any other cultivar and location combination (Table 8). In contrast, 'KM' planted at the HRF along with 'GC', 'GF','GEH', and 'KM' planted at the AES had the lowest SW. The cultivar by location interaction occurred because the SW was almost stable for 'KM' at both locations, while the rest of the cultivars had lower SW when planted at the AES.

'German White' planted at the HRF also had the longest SL at 65.5 cm (Table 8). The shortest SL occurred when 'GC' , 'GF', and 'GEH' were planted at the AES. The cultivar by location interaction occurred because 'KM' and 'GEH' SL decreased approximately 14% and 20%, respectively when planted at the AES while the SL decreased approximately 33% and 30%, respectively when 'GC' and 'GF' were planted at the AES.

Table 8: Effect of cultivar and location on plant fresh weight, plant dry weight, scape length, and scape weight averaged over three planting dates for garlic grown in North Dakota.

Location	Cultivar	PFWb	PDW	SW	SL
		Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
		------------------------g------------------------------------			---------cm--------
HRF[b]	GC[b]	43.7 ± 6.26 de[a]	30.1 ± 3.03 c-e	6.38 ± 0.83 cd	45.5 ± 2.87 cd
	GF	56.3 ± 6.26 cd	31.9 ± 3.03 c-e	7.20 ± 0.83 bc	48.5 ± 2.87 c
	GEH	63.3 ± 8.15 c	36.1 ± 3.94 cd	7.40 ± 1.06 bc	43.4 ± 3.68 c-e
	GW	111 ± 6.78 a	60.1 ± 3.28 a	15.4 ± 0.89 a	65.5 ± 3.10 a
	KM	32.1 ± 7.01 e	21.6 ± 3.39 f	5.58 ± 0.92 c-e	43.9 ± 3.20 c-e
	Mus	64.1 ± 5.98 c	36.5 ± 2.90 c	9.15 ± 0.80 b	57.9 ± 2.77 b
AES	GC	50.0 ± 5.98 cd	26.8 ± 2.90 ef	3.60 ± 0.80 e	30.7 ± 2.77 h
	GF	55.4 ± 5.98 cd	28.5 ± 2.90 d-f	4.75 ± 0.80 de	34.3 ± 2.77 gh
	GEH	58.2 ± 6.26 cd	32.6 ± 3.03 c-e	5.11 ± 0.83 c-e	34.5 ± 2.87 f-h
	GW	103 ± 5.98 ab	53.8 ± 2.90 a	6.32 ± 0.80 cd	41.4 ± 2.77 d-f
	KM	50.1 ± 5.98 cd	27.1 ± 2.90 d-f	5.20 ± 0.80 c-e	37.8 ± 2.77 e-g
	Mus	94.5 ± 5.98 b	45.7 ± 2.90 b	5.93 ± 0.80 cd	39.9 ± 2.77 d-g
P-value		0.0082	0.037	<.0001	0.0177

[a]Means with the same letter for each growth parameter are not significantly different based on Lsmeans at P ≤ 0.05.
[b]Abbreviations: PFW = plant fresh weight, PDW = plant dry weight, SL = scape length, SW = scape weight, AES = Agriculture Experiment Station in Fargo, ND, HRF = Horticulture Research Farm near Absaraka, ND, GC = Georgia Crystal, GF = Georgia Fire, GEH = German Extra Hardy, GW = German White, KM = Koran Mountain, and Mus = Music.

Garlic planted on Sept 28 at the HRF produced the most leaves, averaging 7.6 leaves (Table 9). Delaying the planting at the HRF until Oct 25 resulted in the lowest number of leaves, averaging 5.06 leaves. The planting date and location interaction occurred because at the HRF, the leaf number decreased 3% from early planting date to the mid-planting date and then decreased 31% from mid to late planting, while at the AES, leaf number decreased approximately 7% from early planting date to mid-planting date and decreased approximately 12% from mid planting date to late planting date.

Garlic planted on Sept 28 at the HRF were the tallest plants (71.6 cm) (Table 9). On the other hand, the shortest plants were planted on Oct 25 at the HRF (39.6 cm). The planting date by location interaction occurred because the plant height decreased by approximately 45% from the first to last planting date at the HRF while the plant height decreased only 29% from the first to last planting date at the AES location.

Table 9: Effect of location and planting date on leaf number and plant height averaged over six garlic cultivars grown in North Dakota.

Location	Planting Date	Leaf number	Plant height
		Mean ± SE	Mean ± SE
			------cm------
HRF[b]	Sept 28	7.60 ± 0.12 a[a]	71.6 ± 0.86 a
	Oct 12	7.35 ± 0.12 b	62.7 ± 0.86 b
	Oct 25	5.06 ± 0.15 e	39.6 ± 1.17 e
AES	Sept 28	7.29 ± 0.12 b	64.8 ± 0.86 b
	Oct 12	6.81 ± 0.12 c	56.6 ± 0.86 c
	Oct 25	6.00 ± 0.12 d	46.0 ± 0.86 d
P-value		<.0001	<.0001

[a]Means with the same letter in a column are not significantly different based on Lsmeans at P ≤ 0.05.
[b]Abbreviations: AES = Agriculture Experiment Station in Fargo, ND; HRF = Horticulture Research Farm near Absaraka, ND.

The planting date by location interaction was not significant for PFW (p-value = 0.1953). Only the planting date influenced the PFW with garlic planted on Sept 28 having the greatest PFW (96.7 g). In contrast, garlic planted Oct 25 had the lowest PFW (30.8 g). Location did not influence PFW. The greatest PDW (56.6 g) was when garlic was planted on Sept 28 at the HRF, while the lowest PDW (15.2 g) was when garlic was planted Oct 25 at the HRF, which was a 73% decrease in PDW, even though it was not significantly different from garlic planted Oct 25 at the AES (Table 10). The planting date by location interaction occurred because the PDW decreased rapidly from the earliest planting date to the late planting date at the HRF, whereas the PDW gradually decreased for each planting date when garlic was planted at the AES.

Garlic planted Sept 28 at the HRF had the greatest SW (13.1 g), which was 247% higher than the lowest SW (3.77 g) from garlic planted Oct 25 at the AES, although this SW was not significantly different from garlic planted Oct 25 at the HRF (Table 10). The planting date by location interaction occurred because the plant SW was high for the first planting date at the HRF but then decreased rapidly for the next two planting dates, whereas the plant SW gradually decreased from the first to last planting date at the AES location.

The longest SL was when garlic was planted Sept 28 at the HRF (64 cm), while the lowest SL was when garlic was planted Oct 25 at the AES (Table 10). Just like the PDW planting date and location interaction, the plant SL was high for the first planting date at the HRF but then decreased rapidly for the next two planting dates, whereas the plant SL gradually decreased from the first to the last planting date at the AES location.

Table 10: Effect of planting date and location on plant fresh weight, plant dry weight, scape weight and scape length averaged over six garlic cultivars grown in North Dakota.

Location	Planting	PDWb	SW	SL
	Date	Mean ± SE	Mean ± SE	Mean ± SE
		---------------------- g ---------------------		-------cm-------
HRF[b]	Sept 28	56.6 ± 2.21 a[a]	13.1 ± 0.64 a	64.0 ± 2.16 a
	Oct 12	36.3 ± 2.26 c	8.50 ± 0.65 b	52.6 ± 2.21 b
	Oct 25	15.2 ± 2.87 d	4.00 ± 0.79 de	36.1 ± 2.74 d
AES	Sept 28	49.6 ± 2.21 b	6.42 ± 0.64 c	40.1 ± 2.16 c
	Oct 12	36.7 ± 2.21 c	5.26 ± 0.64 cd	37.6 ± 2.16 c
	Oct 25	20.9 ± 2.26 d	3.77 ± 0.65 e	31.8 ± 2.21 cd
P-value		0.0098	<.0001	<.0001

[a]Means with the same letter for each growth parameter are not significantly different based on Lsmeans at P ≤ 0.05.
[b]Abbreviations: PFW = plant fresh weight, PDW = plant dry weight, SL = scape length, SW = scape weight, AES = Agriculture Experiment Station in Fargo, ND, HRF = Horticulture Research Farm near Absaraka, ND.

Plant yield parameters

The interaction between cultivar and planting date was not significant for CN (P = 0.5632) or BW (P = 0.1372). Cultivar influenced both CN and BW with 'GW' having the highest CN (4.0) and BW (47.8 g). However, the CN for 'GW' was similar to the CN of 'Mus' (3.7). The cultivar with the fewest CN was 'GEH' (3.2). However, this low CN did not differ from the CN for 'GF' (3.3) or 'KM' (3.4). The cultivar with the lowest BW was 'KM' (20.1 g). However, this low BW did not differ from 'GF' (24.0 g) or 'GC' (24.7 g). Planting date also influenced CN and BW with the first planting date resulting in the most cloves (4.3) and BW (42.6 g), with both significantly decreasing for each delay in planting (data not shown).

The interaction between cultivar and planting date influenced BD with the greatest BD (5.36 cm) was when 'GW' was planted on Sept 28, which was 99% higher than the smallest BD (2.70 mm) of 'GEH' planted on Oct 25 (Table 11). However, 'GW' planted Sept 28 had similar BD as 'GW' planted Oct 12, 'Mus' planted Sept 28 and 'GEH' planted Sept 28. In addition, the smallest bulbs from 'GEH' planted on Oct 25 did not differ from 'GF' and 'KM' planted Oct 25. The cultivar by planting date interaction occurred because 'GEH' BD decreased 28% when the planting was delayed from Oct 14 to Oct 25 while 'KM' BD decreased only 14% when the planting was delayed from Oct 14 to Oct 25.

Table 11: Effect of cultivars and planting dates on clove number, bulb diameter, and bulb weight averaged over two locations for garlic grown in North Dakota.

Planting	GC[b]	GF	GEH	GW	KM	Mus
Date	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE	Mean ± SE
BD[b]	-- cm --					
Sept 28	4.51 ± 0.14 b [a]	4.49 ± 0.15 bc	4.95 ± 0.20[a]	5.36 ± 0.27 a	4.31 ± 0.11 b-d	4.98 ± 0.11 a
Oct 12	3.89 ± 0.11 ef	4.00 ±0.17 de	3.76 ± 0.20 e-g	5.13 ± 0.12 a	3.46 ± 0.26 g-i	4.47 ± 0.14 bc
Oct 25	3.14 ± 0.15 hi	3.11 ± 0.14 h-j	2.70 ± 0.18 j	4.17 ± 0.21 c-e	2.99 ± 0.11 ij	3.51 ± 0.18 f-h
P-value	-- 0.0247 --					

[a]Means with the same letter are not significantly different using LSMeans at P ≤ 0.05.
[b]Abbreviations: BD = bulb diameter, GC = Georgia Crystal, GF = Georgia Fire, GEH = German Extra Hardy, GW = German White, KM = Koran Mountain, and Mus = Music.

The interaction of planting date and location was not significant for CN (P = 0.2312). As previously mentioned, planting garlic on Sept 28 resulted in the greatest CN (4.3) while location did not influence CN. Garlic planted on Sept 28 at the HRF had the highest BW (47.9 g) which was 263% higher than the lowest BW (13.2 g) when garlic was planted Oct 25 at the HRF (Table 12). However, the low BW when garlic was planted Oct 25 at the HRF was similar to the BW when garlic was planted Oct 25 at the AES. The planting date and location interaction occurred because the BW decreased 72% from the first to the last planting date at the HRF while the BW decreased 49% from the first to the last planting date at the AES.

The greatest BD (4.89 cm) was when garlic was planted on Sept 28 at the HRF, which was 57% higher than the lowest BD (3.11 cm) when garlic was planted Oct 25 at the HRF (Table 12). However, this low BD was not significantly different from the BD (3.36 cm) when garlic was planted Oct 25 at the AES.

Table 12: Effect of planting date and location on bulb weight and bulb diameter averaged over six garlic cultivars and grown in North Dakota.

Location	Planting date	BW b	BD
		Mean ± SE	Mean ± SE
		--------- g ---------	------cm-----
HRF[b]	Sept 28	47.9 ± 2.00 a[a]	4.89 ± 0.097 a
	Oct 12	30.7 ± 2.04 c	4.08 ± 0.099 c
	Oct 25	13.2 ± 2.71 d	3.11 ± 0.128 d
AES	Sept 28	37.4 ± 2.00 b	4.64 ± 0.097 b
	Oct 12	28.7 ± 2.00 c	4.14 ± 0.097 c
	Oct 25	18.9 ± 2.04 d	3.36 ± 0.099 d
P-value		0.0009	0.0246

[a] Means with the same letter for each growth parameter are not significantly different based on Lsmeans at P ≤ 0.05.
[b] Abbreviations: PFW = plant fresh weight, PDW = plant dry weight, SL = scape length, SW = scape weight, AES = Agriculture Experiment Station in Fargo, ND; HRF = Horticulture Research Farm near Absaraka, ND .

Correlation analysis was conducted to examine the relationship between BW and CN, BW and PFW, BW and PDW, BW and SL, BW and SW, and BW and LN (supplement). The BW and PDW among garlic cultivars evaluated had the strongest positive correlation, with a coefficient of 0.9593, indicating a near-perfect linear relationship between these two variables. On the other hand, the relationship between leaf number and BW across garlic cultivars, revealed the lowest statistically significant positive correlation ($r = 0.4324$, $p < 0.0001$). This suggests that garlic cultivars with higher leaf numbers tend to have higher BW, though the relationship was moderate. Overall, the correlation analysis revealed strong positive relationships between BW and PFW, PDW, BD, and SW, indicating that these traits were strong selection criteria for improving garlic bulb yield while LN, CN, and SL exhibited moderate to low correlations with BW.

Plant yield correlation

A correlation analysis was conducted to examine the relationship between CN and BW among garlic cultivars. The results revealed a moderate positive correlation between the two variables, with a correlation coefficient of 0.6778 (Figure 1). This indicates an upward trend, where an increase in CN is generally associated with an increase in BW, although the association is not strong. The relationship was statistically significant, with a p-value of <0.0001. The scatter plot, along with 70% and 80% prediction ellipses, illustrates this trend. The general upward pattern across 133 observations suggests that CN is a contributing factor to BW in garlic. Most observations were captured within the 80% prediction ellipse, indicating that the model effectively predicted the relationship for most garlic cultivars. Additionally, the data clusters around the CN values ranged from two to five cloves per bulb, which represented the most common range observed. However, a few outliers fell outside the prediction ellipses. These outliers may represent cultivars with unique traits, environmental influences, or potential measurement errors. These outliers are noteworthy as they could highlight special characteristics worth further investigation or suggest additional factors affecting BW that are not directly explained by CN.

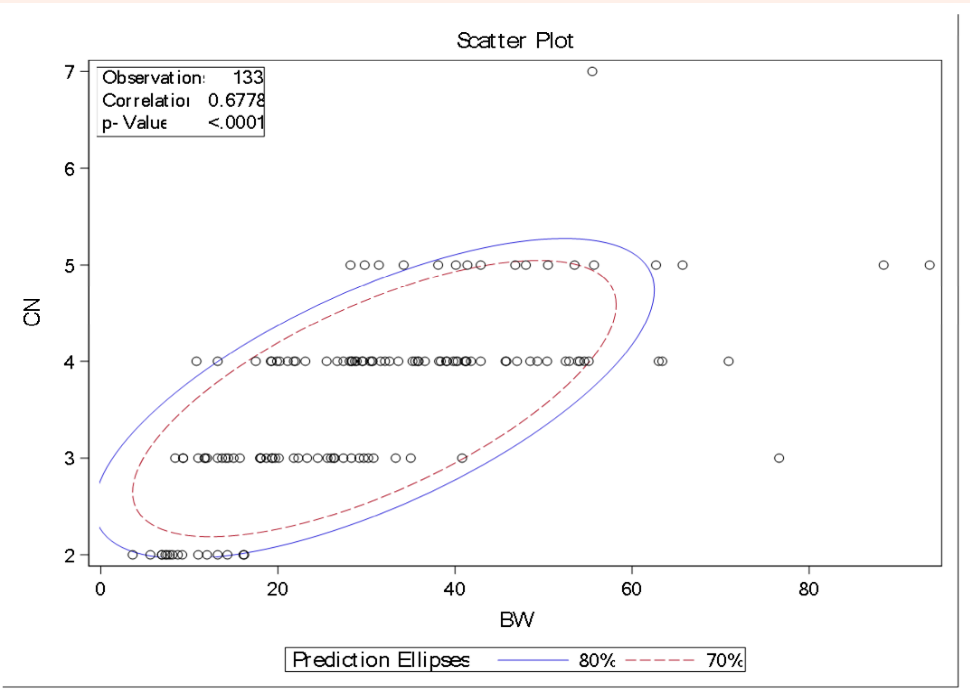

Figure 1: Scatter plot showing the relationship between bulb weight (BW) and clove number (CN) in Garlic Cultivars with 70% and 80% Prediction Ellipses.

A correlation analysis between BW and PFW among garlic cultivars revealed a strong positive correlation, with a coefficient of 0.913, indicating a very close association between the two variables (Figure 2). The relationship was statistically significant, (P < 0.0001). The scatter plot, accompanied by 70% and 80% prediction ellipses, visually demonstrated this strong relationship. The general upward trend in the data indicated that as BW increased, PFW also increased proportionally. This suggests that PFW can be a significant predictor for high yielding garlic bulbs. Most of the data points were concentrated within the 80% prediction ellipse, showcasing the reliability of the model in capturing the relationship between BW and FW for the majority of cultivars. The tighter clustering of points around the center of the ellipses reflected the strength and consistency of this correlation. Additionally, most observations fell within a BW range of approximately 20–60 g, corresponding to PFW values that cluster between 10–150 g. A few outliers were present outside the prediction ellipses, suggesting that certain garlic cultivars may exhibit unique traits or that environmental conditions or measurement errors could have influenced these observations.

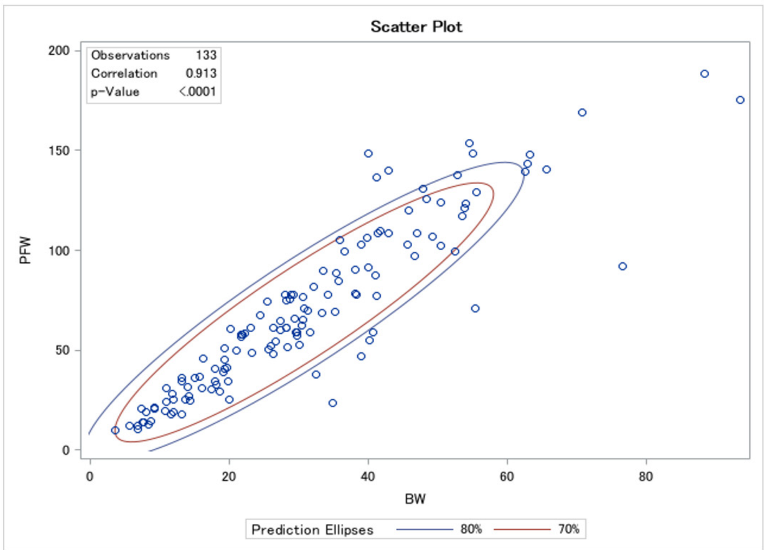

Figure 2: Scatter plot showing the relationship between plant fresh weight (PFW) and bulb diameter (BW) in garlic cultivars with 70% and 80% prediction ellipses.

The BW and PDW among garlic cultivars evaluated revealed a very strong positive correlation, with a coefficient of 0.9593, indicating a near-perfect linear relationship between these two variables and was statistically significant (Figure 3). The scatter plot prediction ellipses visually support this strong relationship. The data points exhibited a clear upward trend, showing that as BW increased, PDW also increased consistently. This result underscores the tight connection between BW and PDW, suggesting that BW is a key determinant of PDW in garlic. The majority of observations fell within the 80% prediction ellipse, demonstrating the model effectiveness in capturing relationship between BW and PDW for most garlic cultivars at a broader spectrum. The clustering of points reflected the strong and consistent nature of this correlation, with BW values primarily ranging between 5 and 60 g and the corresponding PDW values clustering around 5 to 65 g. A few data points lie outside the prediction ellipses, indicating the presence of outliers. These outliers may represent cultivars with unique genetic traits, environmental influences, or potential measurement errors. They can also provide valuable opportunities for further research into factors that could affect BW beyond the direct influence of PDW.

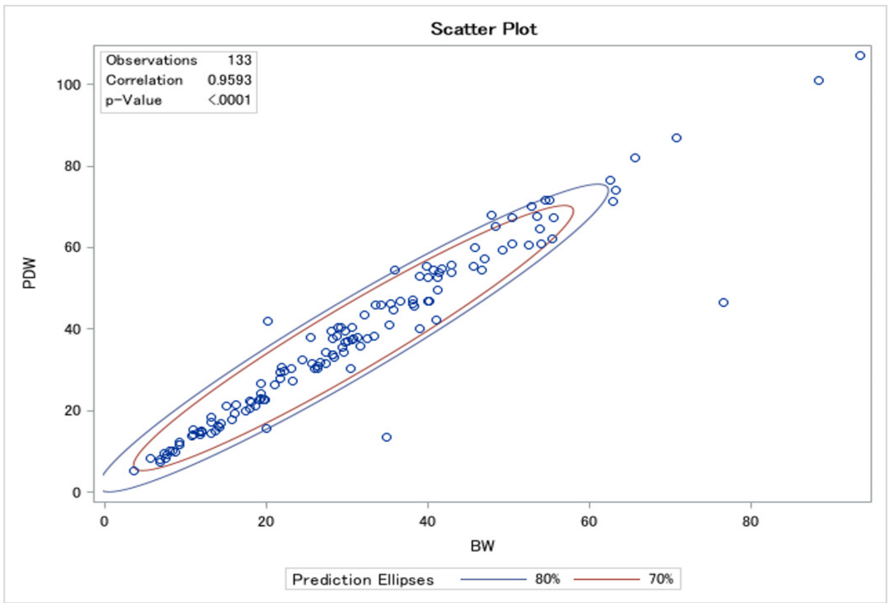

Figure 3: Scatter plot showing the relationship between plant dry weight (PDW) and bulb weight (BW) in garlic cultivars with 70% and 80% prediction ellipses.

A correlation between BW and BD among garlic cultivars showed a strong and positive correlation, with a coefficient of 0.9312, indicating a very strong linear association between the two variables (Figure 4). The relationship was statistically significant, (P < 0.0001). The scatter plot, supplemented by 70% and 80% prediction ellipses, visually depicts this strong relationship. The data showed a clear upward trend, where an increase in BW corresponded to an increase in BD, suggesting that the garlic BD can be used in predicting whether cultivars can provide heavier bulbs. The clustering of points highlights the consistency of the relationship, with BW values primarily ranged from 10 to 60 g and corresponding BD values clustered between 15 and 55 mm. This tight clustering demonstrated a strong predictive relationship between the two variables. A few outliers may be attributed to unique cultivar traits, environmental influences, or potential measurement errors.

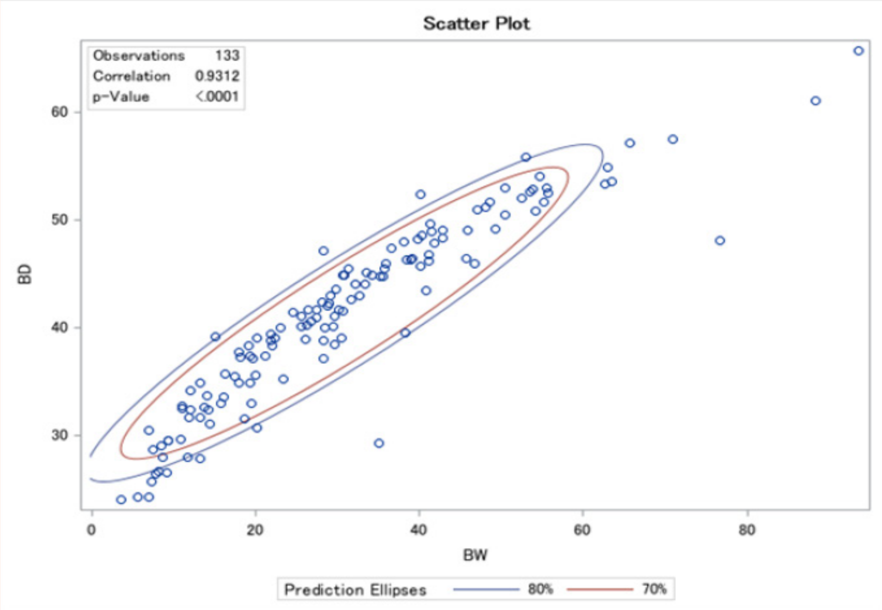

Figure 4: Scatter plot showing the relationship between bulb diameter (BD) and bulb weight (BW) in garlic cultivars with 70% and 80% prediction ellipses.

The correlation between BW and SL indicated a moderate positive correlation, with a correlation coefficient of 0.5902, indicating that there is a tendency for SL to increase as BW increases (Figure 5). The relationship was statistically significant, (P < 0.0001). The data points generally exhibited an upward trend, suggesting a positive association between BW and SL. The majority of the observations were widely dispersed within the 80% ellipse. Few observations were widely spread outside the 80% ellipse which may reflect instances where SL will deviate significantly from what is expected based on the BW. The presence of these outliers may be attributed to unique genetic characteristics, environmental factors, or measurement errors. Such deviations could suggest other variables influencing BW beyond SL.

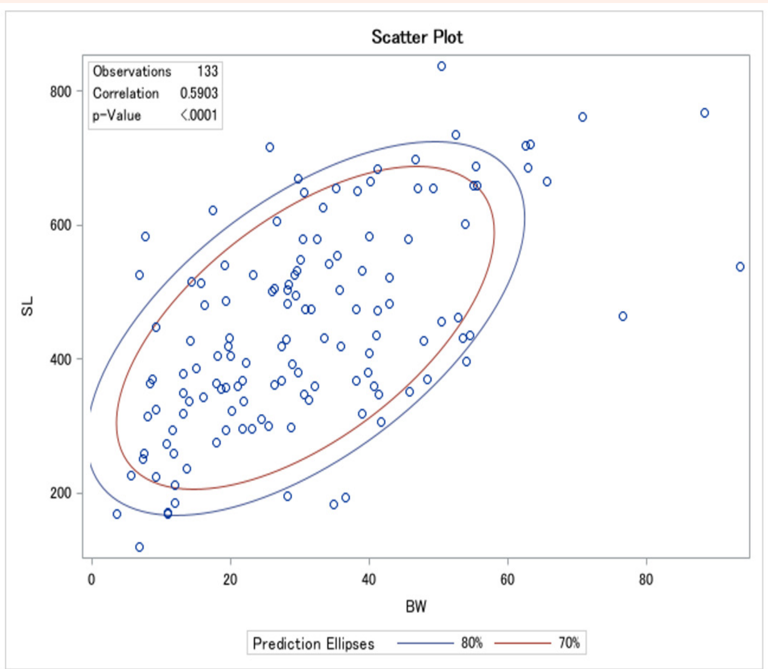

Figure 5: Scatter plot showing the relationship between scape length (SL) and bulb weight (BW) in garlic cultivars with 70% and 80% prediction ellipses.

The scatter plot illustrated the relationship between SW and BW in garlic cultivars, with 70% and 80% prediction ellipses delineating the data distribution (Figure 6). A total of 133 observations were analyzed, revealing a statistically significant positive correlation ($r = 0.7358$, $p < 0.0001$). This indicates a strong linear relationship between SW and BW, where increases in SW are associated with corresponding increases in BW. The 70% prediction ellipse captures a tighter cluster of data points, representing the core relationship between SW and BW with reduced variability. In contrast, the 80% prediction ellipse covers a broader range of observations, accounting for additional variability but maintaining alignment with the overall trend. While most data points fall within the prediction ellipses, a few outliers are apparent. Notably, one extreme data point exhibits an exceptionally high BW (> 80) with a moderate SW. These outliers may reflect unique cultivar characteristics, experimental variability, or environmental influences. The observed positive association suggests that cultivars with higher SW are more likely to produce larger bulbs. This relationship emphasizes the potential importance of SW as a selection criterion for garlic breeding programs or management practices aimed at optimizing bulb yield.

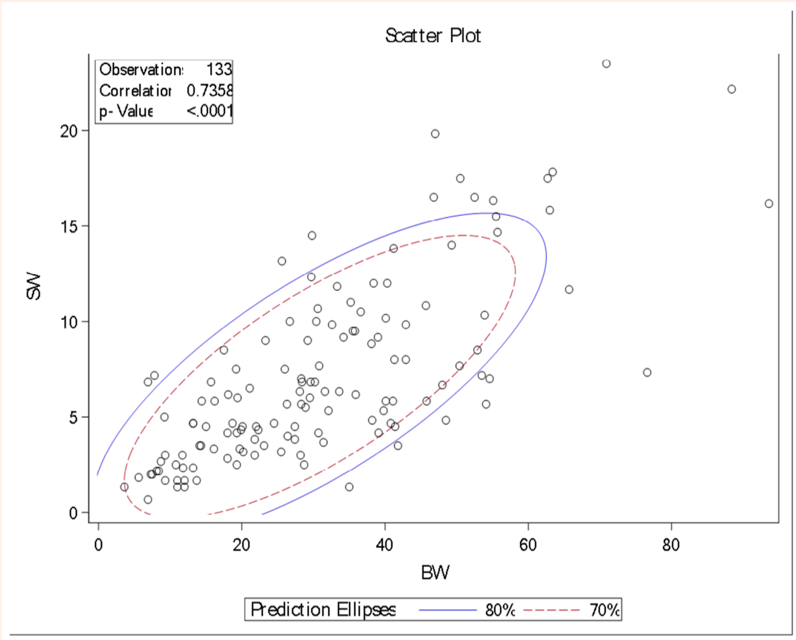

Figure 6: Scatter plot showing the relationship between scape weight (SW) and bulb weight (BW) in garlic cultivars with 70% and 80% prediction ellipses.

The scatter plot displayed the relationship between leaf number and BW across garlic cultivars, incorporating 70% and 80% prediction ellipses to capture the variability within the dataset (Figure 7). A total of 135 observations were included in the analysis, revealing a statistically significant positive correlation ($r = 0.4324$, $p < 0.0001$). This suggests that garlic cultivars with higher leaf numbers tend to have higher BW, though the relationship was moderate. The 70% prediction ellipse represented the core data distribution, with most observations clustering within this tighter boundary, indicating a consistent relationship between leaf number and BW. The 80% prediction ellipse includes additional data points with greater variability, reflecting broader trends in the dataset. It was also noticed that the majority of BW corresponded to plants that produced 7-9 leaves per plant. several outliers are evident, including others with high BW (> 80) and another with a low leaf number (< 4). These deviations may reflect unique cultivar traits, environmental factors, or experimental variability. This result highlighted that leaf number can be a predictor for BW of garlic.

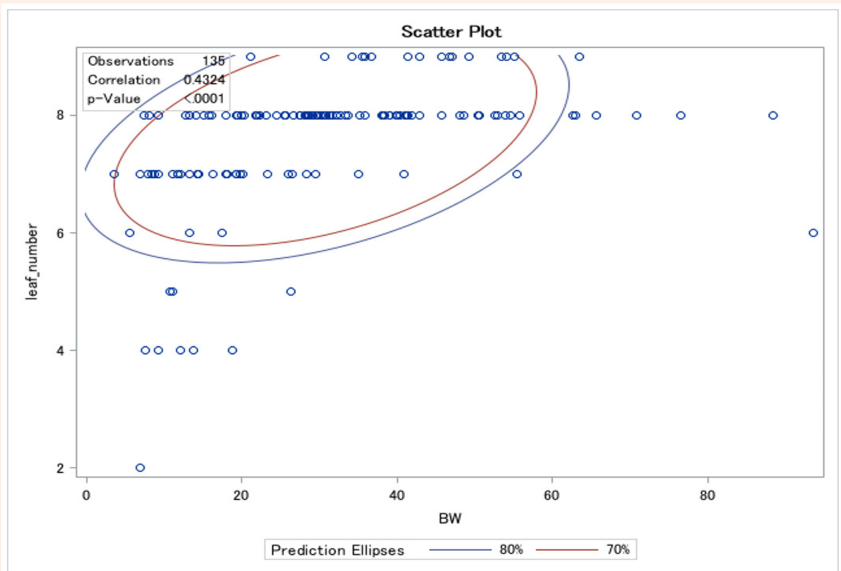

Figure 7: Scatter plot showing the relationship between leaf number and bulb weight (BW) in garlic cultivars with 70% and 80% prediction ellipses

Discussion

Plant growth parameters

The results of this study show the significant influence of cultivar selection and planting date on garlic growth and yield under North Dakota conditions. The PFW, PDW, and SL were affected by the interaction between these two factors whereas SW did not show any significant variation, suggesting that certain traits may be less sensitive to planting date adjustments. The highest PFW and PDW were consistently observed when garlic was planted on Sept 28, particularly for the cultivar 'GW', which outperformed the other cultivars across most measured parameters. These results were consistent with other research showing the importance of early fall planting for maximized fresh and dry biomass accumulation, especially in regions with cold winter temperatures [5,9].

Delaying planting until Oct 25 generally resulted in the lowest PFW and PDW values, as seen with 'GEH.' This result emphasizes the negative effects of late planting on garlic growth, likely due to reduced thermal time and a shortened growing season. This finding was supported by Islam et al. [32], who concluded that early planting influenced total dry matter because the earlier planting provided a longer growth period before bulb initiation, resulting in a larger plant that produced larger bulbs and higher yields [33]. The SL also demonstrated significant sensitivity to planting date, with the longest scapes from 'Mus' and 'GW' when planted on Sept 28 and Oct 12, respectively. These findings suggest that the early fall planting provided sufficient time for early vegetative growth in the spring and scape elongation, which are critical for achieving optimal yields. The lowest SL was recorded for 'Mus' planted on Oct 25, further reinforcing the negative impact of delayed planting [32,33]. Interestingly, scape weight (SW) did not show significant variation across planting dates and cultivars, suggesting that this parameter may be more genetically determined and less influenced by environmental factors or planting time.

The interaction of location and cultivar also influenced garlic growth parameters, including PFW, PDW, SW, and SL. The interaction between these factors was critical for optimizing garlic production under North Dakota's environmental conditions. The results reveal that 'GW' consistently performed better across both locations, recording the highest PFW and PDW at the HRF. These findings also demonstrated the superior adaptability of 'GW' to varying environmental conditions. The higher biomass production at the HRF may be attributed to more favorable environmental factors, such as soil properties or microclimatic conditions, supporting vegetative growth. Furthermore, in most cases, there were no significant differences among the same cultivars grown at the two locations. This lack of variation could be attributed to the minimal differences in average air temperatures between the two locations (Table 1). Such similar temperature conditions likely provided comparable environments for garlic growth, minimizing the impact of location on the performance of individual cultivars. The general better performance of cultivars grown at the HRF compared to the AES may be attributed to the higher soil pH levels of the AES soils. Elevated soil pH can impact nutrient availability and uptake, potentially limiting the growth and development of garlic plants. This may help to explain the reduced performance of certain cultivars in Fargo despite similar average air temperatures across both locations. The 'GW' grown at the HRF demonstrated superior performance, recording the highest SW and SL while at the AES, 'GC' recorded the lowest SW and SL. These cultivar differences for the SW and SL across both locations may also be due to the pH differences as soil pH was high at the AES (Ph=8) as compared to the HRF (Ph=7). The above results were supported by Neina [34], who concluded that nutrient limitations from higher soil pH can negatively impact plant growth and development. The findings from this research indicate that 'GW' was the most adaptable garlic cultivar in North Dakota. This conclusion aligns with information from Urban Farmer [35], which noted that 'GW' garlic was sought after for its adaptability in different climates and its ability to store well. This was further supported by Alsup-Egbers et al. [23].

The combined effect of location and planting date influenced PDW, SW, and SL, but not PFW. The highest PDW was recorded for garlic planted on Sept 28 at the HRF. Similarly, the SW and SL were highest for garlic planted on Sept 28 at the HRF. On the contrary, the lowest values for SW and SL were garlic planted on Oct 25 at the AES. These results reinforce the importance of early fall planting to maximize spring biomass accumulation and scape development. As planting was delayed from Sept 28 to Oct 25, all measured traits showed a significant decline. This trend was consistent across both locations. Delayed planting likely exposed garlic plants to suboptimal root development conditions, which are critical for garlic establishment and development before the onset of dormancy. The observed decrease in SL also supports this, as scape elongation is closely linked to vegetative growth vigor, which was reduced in suboptimal conditions. These findings align with existing studies that emphasize the importance of early planting in garlic production to ensure adequate spring vegetative growth and higher yields [28,36,37]. The differences in performance between the two locations suggest that location-specific factors such as soil properties, microclimate, and management practices influence garlic growth.

The interaction effect of cultivar and location was significant for both leaf number and plant height indicating that the performance of garlic cultivars in terms of vegetative growth varies significantly depending on the location. The highest number of leaves was recorded for the cultivar 'GW' grown at the HRF, whereas the lowest leaf number was observed for 'GEH' grown at the same location. 'German White' impressive performance for both parameters in both locations shows how adaptable the cultivar is to varied conditions. Plant height also varied significantly among cultivars and locations. The tallest plants were 'GW' grown at the HRF, whereas the shortest plants were 'GC' grown at the AES, indicating that environmental conditions in Fargo may be less favorable for this cultivar. The cultivar difference may be due to the fact that some cultivars adapt better to varied location than others [38]. Some of the cultivars are also better in utilizing nutrient and resource for growth than others [39], hence the reason why 'GW' performed better in both locations. The differences due to location may be due to the AES clay loam soils which sometimes have drainage issues and can reduce the oxygen availability to root, stunting garlic growth and development reducing the bulb size at maturity. Furthermore, garlic prefers well drained warm soils for optimal early development which may be a problem in clay loam soils. Also, high soil pH may contribute to lower plant height and leaf number because soil pH >7.5 reduces the availability of key nutrients leading to deficiency in micronutrients (Fe, Mn and Zn and copper) resulting in chlorosis and reduced growth as was observed at the AES location [40-42]. Research has also showed that high soil pH level often indicates excess bicarbonates or sodium ions in the soil which interfere with nutrient uptake resulting in low plant performance and low yield [43].

Location and planting dates interaction was significant for both leaf number and plant height. Results show that early planting enhances leaf number production as compared to late planting. Furthermore, leaf number was higher when planted at the HRF except for Oct 25 at the AES. This poor performance at the AES may be due the poor soil conditions including high soil pH, and wet conditions limiting nutrient availability to plant and affecting plant growth and development as previously discussed. The plant height also decreased with delayed planting across both locations indicating that early planting provides sufficient time for root development before the ground freezes. Also, it suggests that planting early enabled earlier emergence in the spring for plants to receive enough cool weather and shorter day length which enhances the vegetative growth resulting in taller plants [44].

Cultivar and planting date interaction also showed a significant effect on both leaf number and plant height of garlic. The highest leaf number was when 'GW' was planted Oct 12), whereas the fewest leaves was when 'GEH' was planted Oct 25. Early planting provided a favorable spring environment, characterized by an extended cool period and shorter day length, which enhanced meristematic elongation in garlic plants, leading to increased plant height [38]. Furthermore, the differences among cultivars may be attributed to their varying ability to efficiently utilize available environmental resources for growth. Some cultivars may exhibit greater leaf number and height, which in turn expands leaf area, allowing for increased sunlight absorption and enhanced photosynthesis.

Plant leaf numbers were influenced by location and DAE. The pattern at the AES indicated a slow initial leaf development, followed by a significant increase during the mid to late growth stages. Such delayed early leaf production may have implications for overall garlic yield, as the plants allocate substantial energy to vegetative growth during a critical transition from the vegetative phase to bulb formation. This shift in energy allocation could potentially impact bulb development and final yield [45].

Plant height was also influenced by cultivar and DAE while leaf number showed no significant differences. These findings contrast with those of Sultana et al. [38], who reported significant differences in leaf number among cultivars at different DAE. The tallest plants were 'GW' at 80 DAE, while the shortest plants were 'GC' at 30 DAE. The differences in plant height among cultivars are likely due to inherent varietal characteristics, as some cultivars possess traits that allow them to better adapt to environmental conditions and efficiently utilize available resources for growth and development [38]. Planting date and DAE had a significant effect on plant height while there were no differences for leaf numbers. The tallest plants at 80 DAE were planted Sept 28, while the shortest plants were planted on Oct 25 at 30 DAE. This result can be attributed to the longer vegetative growth period provided by early fall planting, allowing plants to emerge earlier and develop more leaves, which enhanced photosynthesis and ultimately led to increased plant height [38,46-48].

Plant yield parameters

The planting date and cultivar interaction influenced garlic bulb characteristics, particularly BD while CN and BW showed no significant interaction between these factors. The highest BD was when 'GW' was planted on Sept 28. This result again demonstrated the advantage of early fall planting that enabled earlier emergence allowing garlic plants to utilize the extended growing period for vegetative growth and nutrient accumulation, and larger bulbs. In contrast, the lowest BD was when 'GEH' was planted on October 25. The results are similar to reports by Islam et al. [32] and El-Zohiri and Farag [33], who have reported that early planting produce large bulbs and by Poldma et al., [46], who reported fall planting outperformed spring planting. Furthermore, the difference among cultivars performance observed may be due to genetic variations among cultivars and their ability to utilize environmental resources that enhance growth and development (light, CO_2, nutrient) [47,48]. However, the CN results were contrary to Vidya [28], which suggests that the garlic type may play an important role in areas with milder winters.

The significant interaction effect of planting date and location on BW and BD indicates that both planting timing and location-specific environmental conditions play critical roles in determining these traits. Although this effect was not significant for CN, it still showed a general declining trend with delayed planting in both locations. The highest BW and BD were garlic planted on Sept 28 at the HRF, whereas the lowest BW and BD were garlic planted on Oct 25 at the same location. Results were attributed to enhanced vigor and crop growth, as early fall planting is crucial for promoting rapid spring vegetative development, including increased plant height, leaf number, and chlorophyll content. These factors contribute to larger bulb size, resulting in higher BW and BD [36,49,50]. Additionally, differences between locations underscore the significance of location-specific environmental factors, such as soil fertility, temperature conditions, and microclimatic variations. Notably, Fargo soils exhibited higher pH levels which may have influenced garlic growth and yield.

The correlation analysis revealed significant relationships between BW and several traits, including CN, PFW, PDW, BD, SL, SW, and leaf number. The PFW and PDW exhibited a strong and positive correlation with BW. This suggests that plants producing more assimilates can translocate them to the bulb as a sink, resulting in higher BW [51]. Additionally, this strong correlation highlights PFW and PDW as potential selection tools for improving garlic yield. In addition, several researchers have reported similar significant positive correlations between BW and BD [52-54]. Plant SW showed a strong positive correlation with BW, while SL had a positive but moderate correlation. The latter result was partially supported by Sandhu et al. [55]. The correlation between CN and BW was moderate, suggesting that CN can be used as a criterion in selecting cultivars for high yield in garlic. Several researchers have also struggled to suggest CN for selecting cultivars for high yield [52,56,57]. The correlation between leaf number and BW was positive but weak, implying that factors beyond leaf number significantly influence BW variability. These findings were consistent with the work of Kumar et al. and Anik et al. [58,59], who emphasized the role of photosynthetic leaf area in bulb development while acknowledging the impact of varietal characteristics and environmental conditions. Correlation emphasizes the importance of traits such as PFW, PDW, SW, and BD as reliable indicators for improving garlic yield, while traits like CN and leaf number may require further exploration to validate their utility in cultivar selection.

Conclusion

Results indicate that 'GW' was the most adaptable cultivar under North Dakota conditions and that early fall planting, particularly around Sept 25, significantly enhanced garlic yield, making it a recommended practice for optimizing production.

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