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Allometric relationships and growth dynamics of quinoa (*Chenopodium quinoa* Willd.) as influenced by sowing date: implications for non-destructive leaf area estimation

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Abstract:

Understanding the allometric relationships between leaf area and other plant traits is essential for non-destructive growth monitoring and efficient crop management. However, no comprehensive study has yet modeled leaf area in quinoa (*Chenopodium quinoa* Willd.) using simple morphological traits across different sowing dates. This study aimed to quantify allometric relationships between leaf area and plant height, leaf dry weight, stem dry weight, panicle dry weight, and total dry matter, and to evaluate whether these relationships are modified by sowing date. A two-year field experiment was conducted with 12 sowing dates under a randomized complete block design with three replications. Leaf area index (LAI) dynamics were described using a logistic model, and allometric relationships were fitted using power-law equations. The results showed that LAI followed a logistic trend across all sowing dates, with maximum values ranging from 2.7 to 7.9. Plant height provided the most reliable prediction of leaf area ($R^2 = 0.83$, $b = 1.2$), followed by leaf dry weight ($R^2 = 0.72$, $b = 0.97$). The allometric coefficients for stem dry weight ($b = 1.54$, $R^2 = 0.74$) and panicle dry weight ($b = 1.95$, $R^2 = 0.71$) showed greater variability. A striking finding was the exceptionally high allometric coefficient ($b = 4.95$) recorded on May 6 of the second year, indicating a pronounced shift in resource allocation toward leaf area expansion. Total dry matter was a weak predictor ($R^2 = 0.54$), likely due to leaf fall during the growing season. The hypothesis that sowing date modifies allometric relationships was confirmed, as evidenced by considerable variation in allometric coefficients across sowing dates. This study provides, for the first time, a comprehensive set of allometric models for quinoa across multiple sowing dates. Plant height and leaf dry weight are recommended as simple, rapid, and non-destructive indicators for leaf area estimation, facilitating improved crop monitoring and management under diverse environmental conditions.

Keywords: Allometric coefficient, Leaf area index, Logistic model, Power-law equation, Titicaca cultivar

Introduction

Quinoa (*Chenopodium quinoa* Willd.) is a facultative halophyte pseudocereal belonging to the family Amaranthaceae, known for its protein-rich seeds and high nutritional value (Hosseini et al., 2020). Quinoa seeds are rich in protein, iron, magnesium, fiber, and vitamin B2, and the plant is recognized as "green caviar" in South American countries due to its exceptional nutritional properties (Martinez et al., 2015). Climate change, water scarcity, and soil salinity are increasingly threatening global food security, particularly in arid and semi-arid regions. Under such conditions, introducing stress-tolerant, high-nutrition crops such as quinoa has been proposed as a viable strategy for sustainable agricultural production (Ruiz et al., 2014; Jacobsen, 2017). According to the Food and Agriculture Organization (FAO), quinoa can be successfully cultivated on marginal and salt-affected lands where conventional crops fail to produce economic yields (Sohrabi et al., 2025).

In crop plants, the allocation of biomass to different organs follows predictable patterns that can be described through allometric relationships. Allometry refers to the differential growth of plant parts relative to each other or to the whole plant, revealing how developmental and environmental factors shape plant morphology (Weiner, 2004; Poorter et al., 2012). Once allometric relationships are established for a given species, they can serve as robust tools for non-destructive estimation of growth parameters, such as leaf area, using simple morphological measurements (Bakhshandeh et al., 2011). Several studies have successfully developed allometric models for major crops, including soybean (Bakhshandeh et al., 2010), chickpea (Pourreza et al., 2007), faba bean (Rahemi Kariaki et al., 2015), and wheat (Maddah Yazdi et al., 2008).

In soybean, Bakhshandeh et al. (2010) reported that leaf area could be accurately estimated from leaf dry weight using power-law equations ($R^2 > 0.92$). Similarly, in chickpea, allometric relationships between leaf area and plant height varied significantly across cultivars, suggesting genetic control over allometric patterns (Pourreza et al., 2007). In faba bean, Rahemi Karizaki et al. (2015) demonstrated that the relationship of node number and stem dry weight with leaf area was stronger compared to other measured parameters. However, allometric relationships vary from one species to another, and therefore the models developed for other crops cannot be directly applied to quinoa, which differs substantially in plant architecture, leaf morphology, and growth

habit. Quinoa exhibits a unique branching pattern and a panicle inflorescence structure, which may fundamentally alter biomass allocation and allometric relationships (Bazile et al., 2016).

Leaf area is a key ecological variable influencing light interception, transpiration, and photosynthetic capacity (Eriksson et al., 2005). Accurate estimation of leaf area is therefore critical for understanding crop responses to environmental conditions. Among indirect methods, allometric relationships offer a practical, non-destructive alternative to direct leaf area measurement (Bakhshandeh et al., 2011).

Despite extensive research on allometric modeling in various crop plants, no comprehensive study has yet been conducted on quinoa to estimate leaf area from simple morphological traits. This gap is particularly significant given the expanding global cultivation of quinoa under marginal environments. Therefore, assuming that leaf area in quinoa is strongly correlated with plant height, leaf dry weight, stem dry weight, panicle dry weight, and total dry matter, and that these allometric relationships are modified by planting date, conducting such a study is essential. Therefore, the objectives of this study were to: (i) quantify allometric relationships between leaf area and plant height, leaf dry weight, stem dry weight, panicle dry weight, and total dry matter in quinoa; and (ii) evaluate whether these relationships remain stable or vary across different planting dates. The derived models can facilitate non-destructive monitoring of quinoa growth and contribute to improved crop management under diverse environmental conditions.

Materials and Methods

Study site

This experiment was conducted in Khalilabad County, Razavi Khorasan Province, Iran, located at 58°17' E longitude, 35°15' N latitude, and an altitude of 975 m above sea level. Khalilabad has an arid climate with hot summers and cold winters. Frost events in the experimental region mostly occur during December and February. Soil sampling and all field experiments were conducted with the permission of the landowner and in accordance with the research guidelines of Gonbad Kavous University.

Experimental design and treatments

The study was carried out as a randomized complete block design (RCBD) with three replications and 12 planting dates over the 2017–2018 and 2018–2019 growing seasons. Planting

dates were applied every 15 days, starting from March 6. The quinoa cultivar used in this study was ‘Titicaca’, which is characterized by a short growth cycle and tolerance to drought and salinity stress. The seeds of quinoa cultivar 'Titicaca' were obtained from the Seed and Plant Improvement Institute, Karaj, Iran

Soil analysis and crop management

Before the start of the experiment, a composite soil sample was collected from a depth of 0–30 cm and sent to a soil laboratory for analysis to determine fertilizer requirements (Table 1). Based on the results, the amount, type, and application method of fertilizers were precisely calculated. During land preparation, 100 kg ha⁻¹ of NPK fertilizer was applied as basal fertilizer. Experimental plots were 2 m wide, consisting of four rows with 50 cm spacing, and each plot was 6 m long. A distance of 1 m was left between adjacent plots and 1.5 m between blocks. Irrigation was applied every 10 days as flood irrigation based on crop water requirement, ensuring that no drought stress symptoms were observed in any of the planting dates.

Table1: Soil field characteristics in the experiment site.

Factor	pH	Ec (dS/m)	Organic matter (%)	Nitrogen (mg/kg)	Phosphorus (mg/kg)	Potassium (mg/kg)	Sand (%)	Silt (%)	Clay (%)
amount	7.81	1.828	0.232	0.021	3.8	232	42	46	12

Growth measurements

To measure leaf area and dry weight, five plants per plot were selected at intervals of 10–15 days from the beginning of emergence and at intervals of 7–10 days from the start of spring. Different plant parts, including leaves, stems, and panicles, were separated. Leaf area was measured using a Delta-T leaf area meter. The separated plant parts were then dried separately in an oven at 70°C until constant weight and weighed.

Leaf area index modeling

Since leaf area index (LAI) follows a logistic equation (Eq.1), the following logistic model was used to describe the changes in LAI against days after planting (Yin et al., 2003):

$$LAI = \left[\frac{(ae^{(-a \times (dap-b))}) \times c}{1 + e^{(-a \times (dap-b))}} \right]^2 \quad (\text{Eq.1})$$

Where d_{ap} is days after planting, a is a constant coefficient representing the maximum LAI (upper asymptote), b is the time at which maximum LAI occurs, and c is a constant coefficient related to the slope of the curve.

Allometric relationships

To describe the allometric relationships between leaf area and plant height, leaf dry weight, stem dry weight, panicle dry weight, and total dry matter, a power-law equation (Eq. 2) was used, which was linearized (Eq. 3) as follows

$$Y=aX^b \quad (\text{Eq.2})$$

$$\ln(Y)=\ln(a)+b\times\ln(X) \quad (\text{Eq.3})$$

Where a is the intercept and b is the slope (allometric coefficient). The equation was fitted and analyzed separately for each planting date, and finally, a single general equation was fitted for all planting dates combined.

Statistical analysis

To compare the accuracy of leaf area estimation equations using different vegetative traits, the coefficient of variation (CV) was used. A lower CV indicates higher accuracy of the equation. Data analysis was performed using SAS statistical software (version 9.3; SAS Institute Inc., Cary, NC, USA). Mean comparisons were conducted using Fisher's least significant difference (LSD) test at the 5% probability level. Graphs were drawn using Microsoft Excel.

Results

Climate conditions

According to Fig. 1, precipitation during March and April of the second growing season exceeded that of the first season. In contrast, air temperatures during the same months were higher in the first year compared to the second. Furthermore, a frost event occurring in late March 2018 led to a reduction in plant population density for the sowing date of March 19. In most months of the second year, both relative humidity and maximum wind speed were greater than those recorded in the first year. The photosynthetically active radiation (PAR) followed a nearly identical pattern across both years. However, PAR during July of the second year was lower than in the first year, which can be attributed to more overcast conditions. Additionally, PAR in April of the first year was higher than in the same month of the second year.

Figure 1. Trend of temperature, rainfall (a), wind speed, humidity (b) and PAR (c) during the experiment period

LAI

Fitting the logistic equation to the data and estimating the regression coefficients confirmed that the model appropriately described changes in LAI across all sowing dates in both growing seasons (Fig. 2; Table 2). In both years and for all sowing dates, leaf expansion proceeded slowly during the initial phase of the leaf growth period, which continued until the emergence of inflorescences. Subsequently, a relatively sharp decline in LAI was observed, driven by the aging, yellowing, and abscission of lower leaves due to shading, as well as the remobilization of assimilates from leaves to developing seeds during the grain-filling stage.

Across all sowing dates, a rapid decrease in LAI occurred coincident with the color change of inflorescences (fruit set). During all growth stages of the first year, the sowing dates of March 19, March 5, April 3, and August 5 exhibited lower LAI values compared to the other sowing dates. In contrast, the highest LAI values were recorded for the August 20, April 18, and May 4 sowing dates (Fig. 2a; Table 2).

The timing of maximum LAI and the maximum LAI value itself varied considerably among sowing dates. Depending on the sowing date, the time required to reach peak LAI ranged from 60 to 80 days after planting. The mean number of days to reach maximum LAI for each successive sowing date was 67, 63, 74, 80, 79, 67, 60, and 59 days after sowing, respectively (Fig. 2b; Table 2). This finding indicates that when plants are exposed to optimal temperatures toward the end of the first growing season, they attain maximum LAI considerably faster (59 and 60 days after sowing) (Fig. 2).

Both the sowing date and the time to reach maximum LAI also influenced the magnitude of the maximum LAI. According to the fitted regression curve, the highest average maximum LAI value (7.9) was observed for the May 4 and August 20 sowing dates. Conversely, the lowest LAI value (2.7) was recorded for the March 19 sowing date. In the second year, the time required to reach maximum LAI ranged between 65 and 82 days after sowing (Fig. 2). In the second year, the highest and lowest LAI values were associated with the March 19 and August 5 sowing dates, respectively (Fig. 2).

Figure 2. Trend of changes of leaf area index in different sowing dates in 2018 (a) and 2019 (b). March 5th (T1), March 19th (T2), April 3th (T3), April 18th (T4), May 4th (T5), May 19th (T6), August 5th (T7), August 20th (T8). 'Lines represent the logistic model fitted to each data set (Table 2).

Table2- Estimated logistic model coefficients (a,b and c) of leaf area index in different sowing dates in 2017-2018 and 2018-2019. Number of Sample (n), LAI_{max} is maximum leaf area, Coefficient of Determination (R²)

Year	Sowing date	n	a±SE	b±SE	c±SE	LAI _{max}	R ²
2018	March 5 th	6	0.02±0.093	2.96±66	38.3±229.4	5.3	0.92
	March 19 th	6	0.01±0.088	2.2±63.03	15.4±121.1	2.7	0.96
	April 3 th	8	0.01±0.07	2.9±73.64	26.2±219.3	3.8	0.89
	April 18 th	8	0.01±0.087	2.5±80.2	42.2±343	7.5	0.92
	May 4 th	7	0.01±0.071	3.2±78.2	58±444.9	7.9	0.93
	May 19 th	6	0.01±0.087	0.8±66.8	9.3±251.5	5.4	0.99
	August 5 th	6	0.01±0.072	2.97±56.2	26.5±201.1	3.6	0.94
	August 20 th	6	0.02±0.086	2.4±59.2	47.3±365.7	7.9	0.94
2019	March 5 th	7	0.01±0.11	1.1±77.9	14±214	6.1	0.98
	March 19 th	7	0.01±0.081	2.5±75.88	40.2±357.7	7.2	0.94
	April 3 ^h	8	0.01±0.076	2.2±65.4	27.5±281.9	5.4	0.94
	April 18 th	9	0.01±0.076	1.1±80	15.9±340.4	6.4	0.99
	May 4 th	7	0.01±0.078	2.4±82.3	29.9±284.4	4.1	0.94
	August 5 ^h	6	0.01±0.078	4±73.5	19.2±118.7	2.2	0.91
	August 20 th	7	0.01±0.087	1.4±70.7	17.7±257.4	5.6	0.97

Plant height

According to Table 3, plant height (cm) in the first growing season ranged from a minimum of 6.46 cm to a maximum of 102 cm, with a mean value of 58.22 cm. In the second season, the minimum, maximum, and mean were 3.93 cm, 84.60 cm, and 34.75 cm, respectively. As shown in Table 4, R² values varied between 0.72 and 0.99, and were consistently high across most sowing dates, suggesting that the model reliably predicts leaf area based on plant height. All regression models were statistically significant ($Pr > F < 0.05$). Furthermore, the coefficient of variation (CV) ranged from 0.98% to 8.40%, indicating satisfactory measurement precision and robustness of the model under varying environmental conditions.

Table 3. Mean, minimum, and maximum values of plant height (cm), leaf dry weight (g·m⁻²), stem dry weight (g·m⁻²), panicle dry weight (g·m⁻²), and total dry matter (g·m⁻²) measured in the experiment.

Year	Trait	Min	Max	Mean
First	Plant height (cm)	6.46	102.00	58.22
	Leaf dry weight (g·m ⁻²)	0.02	12.45	3.23
	Stem dry weight (g·m ⁻²)	0.02	14.25	3.38
	Panicle dry weight (g·m ⁻²)	0.00	23.75	4.03

	Total dry matter (g·m ⁻²)	0.04	49.10	10.64
Second	Plant height (cm)	3.93	84.60	34.75
	Leaf dry weight (g·m ⁻²)	0.07	3.70	1.07
	Stem dry weight (g·m ⁻²)	0.07	5.80	1.24
	Panicle dry weight (g·m ⁻²)	0.00	13.90	2.01
	Total dry matter (g·m ⁻²)	0.15	21.40	4.32

Plant height-based allometric modeling provides a dependable approach for predicting leaf area in quinoa, especially for sowing dates that experience relatively stable environmental conditions. Across the majority of planting dates, the allometric coefficient (b) remained near one (ranging from 0.82 to 1.99), reflecting a proportional pattern of growth between plant height and leaf area. Nevertheless, on certain dates, including March 6 and May 21 of the first growing season (b = 1.9), leaf area expanded at a faster rate than plant height. When comparing the two cropping seasons, the pooled allometric coefficient was estimated at 1.6 for the first year and 1.2 for the second, whereas the R² values were comparable (0.87 in both years). This indicates an inter-annual variation in the strength of the allometric relationship.

Table 4. Estimated parameters (a and b) of the power-law equation (linearized as $\ln(Y) = \ln(a) + b \cdot \ln(X)$) fitted to the relationship between leaf area (cm²) and plant height (cm) for each planting date and pooled across dates and years.

Year	Planting date	n	a ± SE	b ± SE	CV	Pr > F	R ²
2017-18	March 6	4	0.76 ± 0.21	1.99 ± 0.13	4.26	0.0040	0.99
	March 20	4	0.79 ± 0.40	1.40 ± 0.23	3.44	0.0447	0.91
	April 5	6	0.49 ± 0.10	1.30 ± 0.05	1.64	<0.0001	0.99
	April 20	5	0.44 ± 0.48	1.80 ± 0.28	5.95	0.0077	0.93
	May 6	5	0.20 ± 0.47	1.80 ± 0.25	6.27	0.0064	0.93
	May 21	4	0.39 ± 0.11	1.90 ± 0.07	1.64	0.0013	0.99
	August 7	3	0.40 ± 0.30	1.20 ± 0.17	1.14	0.0886	0.98
	August 22	4	0.73 ± 0.19	1.20 ± 0.11	1.38	0.0077	0.98
Pooled (Year 1)		35	0.06 ± 0.17	1.60 ± 0.10	6.73	<0.0001	0.87
2018-19	March 6	5	0.76 ± 0.13	1.60 ± 0.09	3.19	0.0009	0.98
	March 20	5	0.88 ± 0.21	1.10 ± 0.13	4.22	0.0034	0.95
	April 5	6	1.30 ± 0.38	0.82 ± 0.25	1.80	0.0319	0.72
	April 20	7	0.73 ± 0.36	1.20 ± 0.25	8.40	0.0051	0.81

May 6	5	0.85 ± 0.38	1.10 ± 0.29	6.40	0.0311	0.83
August 7	4	0.24 ± 0.07	1.50 ± 0.04	0.98	0.0009	0.99
August 22	5	0.51 ± 0.55	1.30 ± 0.34	4.50	0.0294	0.83
Pooled (Year 2)	37	0.83 ± 0.11	1.20 ± 0.07	5.77	<0.0001	0.87
Pooled (Both years)	72	0.60 ± 0.11	1.20 ± 0.07	7.37	<0.0001	0.83

n: number of observations; R²: coefficient of determination; CV: coefficient of variation (%)

Analysis of the pooled data from both growing seasons yielded an overall allometric coefficient (b) of 1.2 (Fig. 3a; Table 4) and a coefficient of determination (R²) of 0.83. The regression slope indicates that leaf area and plant height increase in a coordinated but non-proportional manner; specifically, a one-unit increase in plant height corresponds to approximately a 1.2-unit increase in leaf area. These findings confirm that the proposed model has a strong capacity to describe the relationship between plant height and leaf area in quinoa.

Figure 3. Linear fit between natural logarithm of leaf area and natural logarithm of plant height (A), leaf dry weight (B), stem dry weight (C), panicle dry weight (D), total dry weight (E).

Leaf dry weight

The present findings demonstrate that quinoa exhibits a stable and predictable allometric pattern when regressing the natural logarithm of leaf area against the natural logarithm of leaf dry weight. As shown in Table 3, average leaf dry weight was $3.23 \text{ g} \cdot \text{m}^{-2}$ in the first year and $1.07 \text{ g} \cdot \text{m}^{-2}$ in the second. Across the majority of sowing dates, the R² values obtained from regression analysis were above 0.99 (Table 5), confirming the high accuracy of the proposed model. Additionally, the coefficient of variation (CV) fluctuated between 1.30% and 8.75%, underscoring the reliability of the measurements.

According to Table 5, the allometric coefficient (b) ranged from 0.89 to 1.62 across various sowing dates, suggesting a largely coordinated and proportional expansion of leaf area relative to leaf dry weight. Pooled analysis over the two growing years yielded an overall b value of 0.97, indicating a positive and progressive relationship. The final fitted regression model was $\ln(Y) = 1.69 + 0.97 \cdot \ln(X)$, with a coefficient of determination of 0.72 (Figure 3 b). This implies that for every unit increase in leaf dry weight, leaf area increases by 0.97 units. Thus, the allometric model

employing leaf dry weight as the predictor variable proves reliable for leaf area estimation in quinoa, especially under sowing dates with more stable environmental conditions.

Table 5. Coefficients (a and b) of the power-law equation $\ln(Y) = \ln(a) + b \cdot \ln(X)$ fitted to the relationship between leaf area (cm²) and leaf dry weight (g·m⁻²) across different planting dates.

Year	Planting date	n	a ± SE	b ± SE	CV	Pr > F	R ²
2017-18	March 6	4	0.92 ± 0.09	1.49 ± 0.07	3.32	0.0025	0.99
	March 20	4	0.90 ± 0.39	1.47 ± 0.33	3.52	0.0047	0.90
	April 5	6	1.04 ± 0.13	1.32 ± 0.01	2.93	0.0002	0.97
	April 20	5	1.14 ± 0.23	1.33 ± 0.20	5.83	0.0072	0.93
	May 6	5	1.10 ± 0.21	1.38 ± 0.17	5.48	0.0043	0.95
	May 21	4	1.06 ± 0.019	1.46 ± 0.17	5.13	0.0130	0.97
	August 7	3	0.66 ± 1.36	1.61 ± 1.15	4.78	0.3938	0.66
	August 22	4	1.83 ± 0.12	0.89 ± 0.10	1.68	0.0114	0.97
Pooled (Year 1)		35	1.08 ± 0.08	1.36 ± 0.06	5.09	<0.0001	0.93
2018-19	March 6	5	1.33 ± 0.14	1.59 ± 0.19	5.00	0.0034	0.96
	March 20	5	1.37 ± 0.12	1.53 ± 0.15	3.49	0.0019	0.97
	April 5	6	1.50 ± 0.10	1.43 ± 0.13	3.00	0.0004	0.96
	April 20	7	1.48 ± 0.09	1.62 ± 0.13	3.42	<0.0001	0.96
	May 6	5	1.81 ± 0.21	1.25 ± 0.49	8.75	0.0843	0.68
	August 7	4	1.36 ± 0.04	1.39 ± 0.05	1.30	0.0016	0.99
	August 22	5	1.98 ± 0.15	1.02 ± 0.21	3.78	0.0170	0.88
Pooled (Year 2)		37	1.62 ± 0.07	1.30 ± 0.09	6.47	<0.0001	0.84
Pooled (Both years)		72	1.69 ± 0.07	0.97 ± 0.07	9.46	<0.0001	0.72

n: number of observations; R²: coefficient of determination; CV: coefficient of variation (%)

Stem dry weight

Examination of the data in Table 3 revealed that stem dry weight fluctuated with a mean of 3.38 (range: 0.02 to 14.25) g·m⁻² in the first year and 1.24 (range: 0.07 to 5.80) g·m⁻² in the second year. According to the results presented in Table 6, the allometric relationship between the natural logarithm of leaf area and the natural logarithm of stem dry weight followed a dynamic growth pattern that varied with sowing date. High coefficients of determination ($R^2 \geq 0.85$) and acceptable coefficient of variation values ($CV \leq 8.6\%$) confirmed the precision and reliability of the model at the 5% significance level. The allometric coefficient (b) exhibited considerable variation, ranging

from 0.78 (March 20) to 2.70 (March 6) in the first year, and from 1.48 (August 22) to 4.27 (May 6) in the second year. This variability suggests that during the second growing season, the plant allocated more resources toward leaf area expansion relative to stem development. Based on the pooled two-year dataset, the final model was fitted as $\ln(Y) = 1.92 + 1.54 \cdot \ln(X)$, with an R^2 of 0.74 (Figure 3c), indicating a positive and progressive allometric relationship. According to this model, a 10% increase in stem dry weight corresponds to an approximate 15.4% increase in leaf area. These findings demonstrate that stem dry weight can serve as a valid indicator for non-destructive estimation of leaf area in quinoa.

Table 6. Coefficients (a and b) of the power-law equation $\ln(Y) = \ln(a) + b \cdot \ln(X)$ fitted to the relationship between leaf area (cm²) and stem dry weight (g·m⁻²) across different planting dates.

Year	Planting date	n	a ± SE	b ± SE	CV	Pr > F	R ²
2017-18	March 6	4	1.05 ± 0.12	2.70 ± 0.26	6.48	0.0094	0.98
	March 20	4	2.23 ± 0.08	0.78 ± 0.14	2.92	0.0320	0.93
	April 5	6	1.77 ± 0.16	1.45 ± 0.22	5.71	0.0028	0.91
	April 20	5	1.62 ± 0.12	1.86 ± 0.20	4.24	0.0028	0.96
	May 6	5	1.58 ± 0.12	1.95 ± 0.20	4.40	0.0022	0.97
	May 21	4	1.48 ± 0.08	2.24 ± 0.14	2.85	0.0040	0.99
	August 7	3	1.98 ± 0.21	1.08 ± 0.38	2.75	0.2163	0.88
	August 22	4	2.23 ± 0.06	1.17 ± 0.09	2.21	0.0059	0.98
Pooled (Year 1)		35	1.68 ± 0.08	1.75 ± 0.13	7.80	<0.0001	0.84
2018-19	March 6	5	1.87 ± 0.15	2.13 ± 0.45	8.64	0.0179	0.88
	March 20	5	1.76 ± 0.17	2.56 ± 0.46	6.26	0.0114	0.91
	April 5	6	1.70 ± 0.18	2.36 ± 0.48	6.28	0.0079	0.85
	April 20	7	1.70 ± 0.10	2.51 ± 0.31	5.28	0.0005	0.93
	May 6	5	1.73 ± 0.11	4.27 ± 0.76	4.57	0.0111	0.91
	August 7	4	1.60 ± 0.10	2.85 ± 0.32	3.66	0.0124	0.97
	August 22	5	2.16 ± 0.13	1.48 ± 0.36	4.32	0.0256	0.85
Pooled (Year 2)		37	1.85 ± 0.05	2.19 ± 0.16	6.57	<0.0001	0.83
Pooled (Both years)		72	1.92 ± 0.05	1.54 ± 0.11	9.18	<0.0001	0.74

n: number of observations; R²: coefficient of determination; CV: coefficient of variation (%)

Panicle dry weight

The allometric relationship between leaf area and panicle dry weight in quinoa followed a dynamic growth pattern that varied with environmental conditions. According to the data in Table 3, mean panicle dry weight declined from 4.03 g·m⁻² in the first year to 2.01 g·m⁻² in the second year, indicating a significant environmental impact on reproductive organ development. Regression analysis performed on log-transformed data using the power-law model revealed variable accuracy across different sowing dates (R² ranging from 0.48 to 0.99), with the highest value observed on August 7 of the first year. Meanwhile, the coefficient of variation (CV) ranged from 1.69% to 11.26% (Table 7). The allometric coefficient (b) spanned a wide range (0.86 to 4.95), revealing substantial shifts in resource allocation patterns. Notably, for the May 6 sowing date, this coefficient increased from 1.73 in the first year to 4.95 in the second year, suggesting accelerated leaf area growth relative to panicle development in response to changing environmental conditions. The final model derived from the pooled dataset, expressed as $\ln(Y) = 1.43 + 1.95 \cdot \ln(X)$ with an R² of 0.71 (Figure 3 d), confirmed a positive and progressive relationship between the two variables. These findings support the potential use of panicle dry weight as an indicator for leaf area estimation; however, the considerable variability observed in model parameters underscores the need to consider genotype-by-environment interactions when modeling growth in quinoa.

Table 7. Coefficients (a and b) of the power-law equation $\ln(Y) = \ln(a) + b \cdot \ln(X)$ fitted to the relationship between leaf area (cm²) and panicle dry weight (g·m⁻²) across different planting dates.

Year	Planting date	n	a ± SE	b ± SE	CV	Pr > F	R ²
2017-18	March 6	4	1.08 ± 0.19	2.50 ± 0.29	7.67	0.0131	0.97
	March 20	4	2.09 ± 0.11	0.96 ± 0.18	3.05	0.0350	0.93
	April 5	6	1.94 ± 0.18	1.16 ± 0.24	7.42	0.0080	0.86
	April 20	5	1.72 ± 0.10	1.64 ± 0.17	4.14	0.0026	0.96
	May 6	5	1.77 ± 0.17	1.73 ± 0.28	6.98	0.0089	0.92
	May 21	4	1.56 ± 0.15	2.25 ± 0.29	5.64	0.0157	0.97
	August 7	3	2.01 ± 0.005	0.86 ± 0.009	0.08	0.0067	0.99
	August 22	4	2.35 ± 0.07	1.03 ± 0.11	1.69	0.0115	0.98
Pooled (Year 1)		35	1.78 ± 0.09	1.56 ± 0.14	8.79	<0.0001	0.79
	March 6	5	1.57 ± 0.15	2.23 ± 0.35	6.63	0.0080	0.93
	March 20	5	1.89 ± 0.29	2.06 ± 0.75	11.26	0.0716	0.71

2018-19	April 5	6	1.63 ± 0.17	2.44 ± 0.44	5.72	0.0054	0.88
	April 20	7	1.75 ± 0.13	2.45 ± 0.42	7.02	0.0021	0.87
	May 6	5	1.72 ± 0.12	4.95 ± 0.91	4.72	0.0122	0.91
	August 7	4	1.78 ± 0.24	2.10 ± 0.70	9.91	0.0950	0.82
	August 22	5	2.36 ± 0.21	0.81 ± 0.48	8.03	0.1931	0.48
Pooled (Year 2)		37	1.93 ± 0.07	1.77 ± 0.20	9.01	<0.0001	0.69
Pooled (Both years)		72	1.95 ± 0.05	1.43 ± 0.11	9.66	<0.0001	0.71

n: number of observations; R²: coefficient of determination; CV: coefficient of variation (%)

Total dry weight

The allometric relationship between the natural logarithm of leaf area and the natural logarithm of total dry matter in quinoa followed a complex pattern strongly influenced by sowing date and environmental conditions. Based on the data in Table 3, mean total dry matter decreased from 10.64 g·m⁻² in the first year to 4.32 g·m⁻² in the second year, reflecting an adverse environmental impact on plant productivity in the second growing season. Log regression analysis (Table 8) revealed that model accuracy varied widely across sowing dates, with coefficients of determination ranging from 0.15 (April 5 of the second year) to 0.88 (August 7 of the second year). This substantial variation in model precision can be attributed to environmental factors such as temperature stresses, moisture fluctuations, and nutritional variations. Meanwhile, the allometric coefficient (b) also exhibited pronounced inter-annual differences, increasing from 0.39 in the first year to 2.37 in the second year (Table 8), indicating a shift in plant growth strategy toward greater leaf area development during the second year. The overall model derived from the pooled two-year dataset was fitted as $\ln(Y) = 2.17 + 0.90 \cdot \ln(X)$, according to which a one-unit increase in total dry matter corresponds to a 0.90-unit increase in leaf area (Figure 3e). Collectively, these findings indicate that although a positive and significant relationship exists between leaf area and total dry matter in quinoa, the considerable fluctuations in model parameters underscore the necessity of incorporating genotype-by-environment interactions into growth models for this crop. Furthermore, they suggest that applying a fixed model across all environmental conditions may lead to inaccurate estimations.

Table 8. Coefficients (a and b) of the power-law equation $\ln(Y) = \ln(a) + b \cdot \ln(X)$ fitted to the relationship between leaf area (cm²) and total dry matter (g·m⁻²) across different planting dates.

Year	Planting date	n	a ± SE	b ± SE	CV	Pr > F	R ²
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2017-18	March 6	4	1.87 ± 0.64	1.13 ± 0.86	34.83	0.3209	0.46
	March 20	4	2.40 ± 0.20	0.39 ± 0.31	8.68	0.3346	0.44
	April 5	6	2.31 ± 0.24	0.68 ± 0.31	13.15	0.0905	0.55
	April 20	5	2.11 ± 0.18	1.02 ± 0.29	10.01	0.0383	0.80
	May 6	5	2.07 ± 0.21	1.23 ± 0.35	1.22	0.0384	0.80
	May 21	4	2.08 ± 0.34	1.31 ± 0.67	18.68	0.1893	0.65
	August 7	3	2.38 ± 0.08	0.45 ± 0.16	2.83	0.2234	0.88
	August 22	4	2.64 ± 0.17	0.50 ± 0.25	6.46	0.1852	0.66
Pooled (Year 1)		35	2.20 ± 0.09	0.88 ± 0.14	13.30	<0.0001	0.52
2018-19	March 6	5	2.01 ± 0.21	1.00 ± 0.36	13.41	0.0711	0.71
	March 20	5	2.25 ± 0.26	1.00 ± 0.57	14.86	0.1804	0.50
	April 5	6	2.36 ± 0.25	2.37 ± 0.44	15.41	0.4530	0.15
	April 20	7	1.90 ± 0.15	1.53 ± 0.36	9.09	0.0079	0.78
	May 6	5	2.07 ± 0.12	1.34 ± 0.50	8.41	0.0741	0.71
	August 7	4	1.86 ± 0.19	1.46 ± 0.50	9.02	0.0780	0.85
	August 22	5	2.36 ± 0.15	0.66 ± 0.28	6.61	0.0994	0.65
Pooled (Year 2)		37	2.14 ± 0.07	0.92 ± 0.15	11.07	<0.0001	0.53
Pooled (Both years)		72	2.17 ± 0.05	0.90 ± 0.09	12.14	<0.0001	0.54

n: number of observations; R²: coefficient of determination; CV: coefficient of variation (%)

Discussion

The results of this study demonstrated that LAI in quinoa followed a logistic trend, increasing over time and then declining with the onset of leaf senescence. Overall, the pattern of LAI dynamics was similar across all sowing dates and both growing seasons. Initially, leaf development progressed slowly, a trend that continued until panicle emergence. Thereafter, the rate of leaf area expansion increased and persisted until the maximum LAI was attained. As the plant entered the grain-filling stage and lower leaves began to senesce, LAI experienced a rapid decline. In the first year, the highest mean maximum LAI values (7.9) were recorded for the May 6 and August 22 sowing dates, whereas the lowest value (2.7) was observed on March 20. In the second year, the maximum LAI was highest for the March 20 sowing date and lowest for mid-August. These findings indicate a substantial influence of sowing date on both the maximum LAI and the time required to reach it, such that sowing dates coinciding with the cooler period of the year attained maximum LAI more rapidly (59–60 days after planting) (Jacobsen, 2003; Shahbandeh, 2021).

Plant height, as a key trait in crop plants, is influenced by a combination of genetic, hormonal, and environmental factors (Li et al., 2024). Allometric analyses in this study revealed a significant relationship between leaf area and plant height in quinoa. Based on the pooled two-year dataset, the coefficient of determination (R^2) was 0.83, and the allometric coefficient (b) was 1.2, indicating that leaf area increased 1.2-fold for each unit increase in plant height. A b-value greater than unity suggests that leaf area exhibited a higher relative growth rate compared to height, implying that as plant height increases, leaf area expands at a disproportionately greater rate. Poorter et al. (2012) also confirmed this pattern in many plant species, particularly during active vegetative growth stages. This phenomenon reflects the plant's concurrent investment in both photosynthetic area and vertical growth to compete for light capture (Hosseini et al., 2020). This finding aligns with previous studies on annual crops such as soybean, chickpea, and wheat, which have reported similar allometric relationships. The observed relationship, characterized by a low coefficient of variation and high statistical significance ($P < 0.05$), can be introduced as a reliable indicator for non-destructive leaf area estimation in quinoa. Although a comparison between the two years showed that environmental conditions could affect the intensity of this relationship, the overall pattern of coordinated growth between the two traits remained consistent. Therefore, plant height can serve as a simple, rapid, and practical indicator for leaf area estimation. These findings are consistent with those of Soltani et al. (2016) on wheat, who reported strong allometric relationships between leaf area and height until the flag leaf sheath swelling stage ($R^2 = 0.85$). However, the differences in allometric coefficients between the two experimental years underscore the importance of considering environmental and management factors in growth modeling. The significant effect of sowing date and varying environmental conditions on allometric coefficients observed in this study is consistent with general findings in this field. For example, a study on *Malva parviflora* demonstrated that allometric relationships between height and leaf dimensions differed significantly between cool and warm bioclimatic regions (Eideh & Elkarmi, 2005). In the cool region, height growth was prioritized, whereas resource allocation patterns differed in the warm region. These observations confirm that environmental conditions can drive plants toward either greater leaf area expansion (faster leaf area growth relative to height) or, conversely, prioritize height growth.

The results of this study indicate the existence of a stable and accurate relationship between leaf area and leaf dry weight in quinoa. The pooled two-year allometric coefficient (b) of 0.97 and R^2

of 0.72 suggest that increases in leaf dry weight are accompanied by a relatively constant proportional increase in leaf area, and the model was able to predict leaf area variation with acceptable accuracy. This finding is consistent with results from similar studies on pseudocereals (Shahbandeh, 2021; Jacobsen, 2003) and emphasizes the utility of measurable plant organs for allometric modeling. Leaf dry weight, as a key trait in crop plants, is influenced by genetic, physiological, and environmental factors (Huang et al., 2019). Research has demonstrated very close relationships between leaf area and leaf dry weight that can be estimated rapidly and accurately. The ease of measuring leaf area and leaf dry weight in the field renders this model a practical tool (Rahemi Karizaki et al., 2015). Previous studies have also confirmed the effectiveness of power-law equations in describing allometric relationships. Bakhshandeh et al. (2011) used the equation $Y = aX^b$ to describe the relationship between leaf area and the number of leaves on the main stem of wheat, reporting R^2 values above 0.88. Rahemi Karizaki et al. (2006) employed the same power-law equation to describe the relationship between leaf area and node number on the main stem, leaf dry weight, vegetative component dry weight, and plant height in chickpea. High R^2 values (up to 0.99) under certain conditions indicate the model's strong predictive power, whereas lower R^2 values suggest the influence of unknown factors such as environmental stresses or nutrient availability (El Hassouni et al., 2024). For instance, on August 7 of the first year ($R^2 = 0.66$) and May 6 of the second year ($R^2 = 0.68$), a marked reduction in model accuracy was observed, likely attributable to environmental stresses such as temperature fluctuations or humidity variations during those periods. This pattern is consistent with previous studies on crops such as chickpea and wheat, which have reported similar allometric relationships.

A noteworthy finding was the stability of the b-coefficient under certain conditions, indicating a uniform influence of the predictor variables. This observation aligns with the importance of precise sampling for allometric relationships between leaf dry weight and leaf area (Huang et al., 2019). The allometric model based on leaf dry weight is a suitable tool for estimating leaf area in quinoa, particularly for sowing dates characterized by stable environmental conditions. However, fluctuations in allometric coefficients and R^2 values between years and across different sowing dates highlight the necessity of accounting for environmental and management factors (such as temperature and humidity stresses, irrigation, and fertilization) when interpreting results. Ramesh et al. (2017) and Praveen Kadam et al. (2018) showed in their studies on quinoa that LAI varies under different environmental conditions and sowing dates. These changes may reflect the plant's

priority in developing photosynthetic structures for light capture during early growth stages. Furthermore, the observed differences between the two growing seasons are likely attributable to climatic or management variations, such as differences in irrigation or fertilization practices.

The results showed that the allometric relationships between leaf area and both stem dry weight and panicle dry weight were positive and progressive, although they exhibited greater variability compared to the relationships with plant height and leaf dry weight. The allometric coefficients for leaf area with stem dry weight ($b = 1.54$, $R^2 = 0.74$) and with panicle dry weight ($b = 1.95$, $R^2 = 0.71$) differed, indicating variation in biomass allocation patterns among plant organs. A particularly striking observation was the exceptionally high allometric coefficient ($b = 4.95$) recorded on May 6 of the second year (Table 7), indicating that leaf area expanded nearly five times faster than panicle dry weight. Such a pronounced shift in resource allocation suggests that under the specific environmental conditions of that sowing date—likely a combination of favorable temperature and photoperiod—the plant prioritized leaf area development to maximize light capture at the expense of reproductive organ growth. The higher variability observed for stem and panicle dry weight is likely due to the sensitivity of these organs to environmental conditions and the distribution patterns of photosynthates. This finding is consistent with studies on cereals such as wheat and maize, which have reported the role of stem reserves in grain yield determination (Singh et al., 2010; Petrus et al., 2010). It has also been reported that environmental factors such as temperature and humidity can modulate growth relationships (Noulas et al., 2017). A positive relationship between leaf area and panicle dry weight in quinoa has been previously confirmed (Chen et al., 2023) and is likely associated with increased photosynthetic capacity in plants with larger leaf areas. The relatively lower R^2 values observed in some treatments suggest that variables such as soil moisture, genotype, and irrigation management can affect the accuracy of allometric models (Razzaghi et al., 2020). Moreover, sowing date plays a crucial role in these relationships: early sowing, by extending the vegetative growth period, increases both leaf area and panicle dry weight, whereas late sowing restricts growth and biomass allocation (Sileshi et al., 2023; Talebnejad et al., 2022).

Total dry matter, as a key measure of plant biomass, is influenced by genetic, environmental, and management factors (Cox, 1979). Despite its relatively lower accuracy ($R^2 = 0.54$), the allometric model based on total dry matter remains a useful tool for estimating leaf area in quinoa, considering that approximately half of the variation in leaf area is not explained by total dry weight.

However, the wide fluctuations in allometric coefficients and R^2 values across sowing dates and years clearly indicate the need to consider environmental, management, and physiological factors when interpreting the data. This relationship was weaker than those observed for other traits (such as plant height or leaf dry weight), and this weakness may be attributed to leaf fall during the growing season and the consequent impossibility of collecting all leaves. Lower leaves gradually yellow and abscise, and total plant dry weight can only be measured based on the remaining leaves and stems; therefore, accurate estimation of total dry weight is not feasible. This limitation reduces the accuracy of allometric models based on total dry matter and suggests that for non-destructive LAI estimation, the use of specific and stable organs, such as plant height or fresh leaf weight, is more accurate and practical. This finding is consistent with previous studies on pseudocereals and emphasizes the importance of selecting appropriate indicator organs for allometric modeling (Shahbandeh, 2021; Jacobsen, 2003). Future research should focus on validating the proposed allometric models under different climatic conditions and integrating additional variables such as soil moisture, nutrient availability, and genotype-specific responses to improve predictive accuracy across diverse environments.

Conclusion

The results of this study identified plant height as the most efficient indicator for non-destructive leaf area estimation in quinoa, owing to its ease of measurement and the highest correlation with leaf area. Plant height provided the greatest predictive power, with a coefficient of determination (R^2) of 0.83 and an allometric coefficient (b) of 1.2. Leaf dry weight also offered acceptable accuracy for leaf area estimation ($R^2 = 0.72$). In contrast, the use of total dry matter was less accurate ($R^2 = 0.54$), due to leaf fall during the growing season and the difficulty of complete data collection. The hypothesis that planting date modifies allometric relationships was confirmed, as evidenced by the considerable variation in allometric coefficients across sowing dates, including an exceptional b value of 4.95 recorded on May 6 of the second year. This study provides, for the first time, a comprehensive set of allometric models for quinoa across multiple sowing dates, filling a significant knowledge gap in the literature. The derived models can be applied for growth simulation, optimization of field management, and yield improvement in quinoa. A limitation of this study was the reduced accuracy of the total dry matter model due to leaf fall; future research should focus on validating these models under different climatic

conditions and incorporating additional variables such as soil moisture and nutrient availability to improve predictive accuracy.

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Author contribution

M.T. and A.R.K. conceived and designed the experiments. M.T. performed the experiments and collected the data. A.R.K., A.B., B.T., and E.G.A. analyzed the data and interpreted the results. M.T. and A.R.K. wrote the main manuscript text. All authors reviewed and approved the final manuscript.

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Competing interests

The authors declare no competing interests.

Data availability statement

The datasets generated and/or analysed during the current study are available from the corresponding author on reasonable request.

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Figure legends

Figure 1. Trend of temperature, rainfall (a), wind speed, humidity (b) and PAR (c) during the experiment period

Figure 2. Trend of changes of leaf area index in different sowing dates in 2018 (a) and 2019 (b). March 5th (T1), March 19th (T2), April 3th (T3), April 18th (T4), May 4th (T5), May 19th (T6), August 5th (T7), August 20th (T8). 'Lines represent the logistic model fitted to each data set (Table 2).

Figure 3. Linear fit between natural logarithm of leaf area and natural logarithm of plant height (A), leaf dry weight (B), stem dry weight (C), panicle dry weight (D), and total dry weight (E).