

Competitive Performance of *Chenopodium quinoa* Genotypes in Competition With Weed Species

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Abstract

The study of competitive ability between crops and weeds is relevant for the adoption of more sustainable control methods, with lower costs for producers and less environmental impact. In this context, the objective of this work was to evaluate the competitive ability of quinoa genotypes (Q 1303, Q 1324, and Q 1331) in association with the weeds *Euphorbia heterophylla* and *Urochloa plantaginea* in different plant proportions within the association. The experiment was conducted in a randomized block design with four repetitions. The treatments were distributed in proportions (100:0, 75:25, 50:50, 25:75, and 0:100%) of crop and/or weed plants corresponding to 20:0, 15:5, 10:10, 5:15, and 0:20 plants per pot. The competitiveness of the species was analyzed through diagrams applied to substitution experiments and through relative competitiveness indices. Fifty days after species emergence, measurements were made on tillering of *U. plantaginea*, number of leaves of quinoa and/or *Euphorbia*, plant height, stem diameter, chlorophyll index, gas exchange, leaf area, dry mass of the aerial part, as well as the measurement of nitrogen and phosphorus concentrations in the crop leaves. Heavy interspecific competition occurred between quinoa genotypes the weeds, with mutual harm to the species involved in the community. *U. plantaginea* proved to be more aggressive to quinoa compared to *E. heterophylla*. The quinoa genotypes showed similar competitive abilities, with emphasis on Q1303, which showed greater tolerance to association with *U. plantaginea*. The most detrimental competition for quinoa was interspecific, indicating the need for control of *E. heterophylla* and *U. plantaginea* even at low infestation levels.

Keywords: competitive interaction, *Euphorbia heterophylla*, plant community, *Urochloa plantaginea*

1. Introduction

Quinoa (*Chenopodium quinoa* Willd), belonging to the Chenopodiaceae family and the Chenopodioideae sub-family, originates from the Andes, where it is known as quinua and has been cultivated for many years (Voronov et al., 2023). It is an annual plant with a growth cycle of 80 to 150 days, and its seeds are rich in nutritional val-ues, such as protein, iron, phosphorus, and other essential nutrients for a healthier life (Borges et al., 2016). This crop is also referred to as a pseudocereal because it contains carbohydrates, lipids, proteins, and fibers similar to those found in wheat (Vilcacundo & Hernández-Ledesma, 2017). Quinoa has advantages over other cereals due to its high levels of vitamins like riboflavin, niacin, thiamine, B6, and minerals such as magnesium, zinc, copper, iron, manganese, and potassium compared to other cereal species (Filho et al., 2017).

Among the factors that could hinder the spread of quinoa cultivation in Brazil, the large number of weed species stands out, such as *E. heterophylla* (wild poinsettia) and *U. plantaginea* (Alexandergrass), which can infest the crop. *E. heterophylla* is a species with highly variable morphology and is one of the most invasive weeds in various crops, especially in tropical and subtropical regions of the Americas (Calero et al., 2023). It is a plant

with a C₃ metabolism and a short cycle, well adapted to different environments, with the potential for more than one generation per year, which increases the seed bank in the soil (Xavier et al., 2013; Calero et al., 2023). Additionally, it is resistant to herbicides that inhibit ALS, PROTOX, and EPSPs (Heap, 2026), making chemical control more difficult when it infests agricultural crops (Mendes et al., 2020; Pereira et al., 2022).

U. plantaginea is another likely competitor with quinoa, as it is a species well adapted to the current cropping systems adopted in recent years with other crops, particularly due to the monoculture of corn, soy, and beans (Araújo et al., 2018). This weed is a grass species with rapid growth and development, showing a high competitive ability when infesting agricultural crops. It has a great capacity for tillering, seed production, and uses C₄ metabolism, making it very efficient in the use of water, light, and CO₂. It also produces a large amount of biomass and releases allelopathic substances that interfere with the growth and development of other plants (Vidal et al., 2010; Bastiani et al., 2016; Ferreira et al., 2021).

Weeds compete with crops for water, space, light, and nutrients, in addition to being hosts for insects and diseases that affect other species. This is no different for *E. heterophylla* and *U. plantaginea* (Costa & Rizzardi, 2015; Gonzalez-Andujar et al., 2023; Maciel et al., 2025; Galon et al., 2025). Quinoa is a crop with low competitive ability against weeds, particularly during the early establishment phase, around 30 days after emergence, a period during which the crop shows slow growth and development (García-Parra et al., 2020) and thus requires effective weed control during this stage.

In this context, research that allows for the determination of competitive ability between quinoa genotypes and weeds becomes relevant for the adoption of more sustainable and/or alternative management methods to chemical control, or even the adoption of integrated weed management. Studies that determine the competitive ability of species in a community are essential since the population of cultivated plants is generally constant, while the weed population varies according to the soil seed bank, environmental conditions, and crop management practices that alter infestation levels (Bianchi et al., 2006; Gonzalez-Andujar et al., 2023; Savić et al., 2025). Therefore, it is important to verify the influence of variation in plant proportions between species, as the density of weeds is the factor that most affects the growth and development of crops, often leading to reduced productivity or lower-quality grain production.

Genotypes respond differently to abiotic or biotic stresses due to the distinct genetic characteristics they possess, such as growth habit, development, root system, leaf area index, plant architecture, biomass production, plant height, leaf number, stem diameter, among others, which directly affect competitive ability (Bastiani et al., 2016; Castro et al., 2019; Savić et al., 2025). When a species has a higher capacity to absorb and assimilate available resources in a given space or ecological niche, its growth and development potential will be higher, as more resources are available in the environment, thus exhibiting superior competitiveness compared to its neighbors, as fewer resources remain in the environment (Agostinetto et al., 2013; Gonzalez-Andujar et al., 2023; Galon et al., 2025; Savić et al., 2025).

To determine relative interactions when plants coexist in communities, special methodologies are necessary, such as substitution experiments, which establish cause-and-effect relationships of competition in the proportions of plants when they are associated (Bianchi et al., 2006). In field conditions, the effect of a weed on a crop is primarily due to the level of infestation and not to its individual competitive ability (Bianchi et al., 2006; Savić et al., 2025). However, when there is competition between individuals of the same genus and/or species, the competitive advantage of the crop may change, as both are exploiting the same ecological niche. Understanding competitive interactions between plants is crucial for ecologists and agronomists to develop sustainable weed management strategies and optimize environmental resource use (Savić et al., 2025).

The hypothesis of this study is that *E. heterophylla* and *U. plantaginea* adapt better to the environment and present higher competitive ability compared to quinoa, particularly when plant proportions are equal, thus utilizing the available resources in the environment more effectively. Therefore, the objective of this study was to evaluate the competitive ability of quinoa genotypes (Q 1303, Q 1324, and Q 1331) in association with the weeds *E. heterophylla* and *U. plantaginea* in different plant proportions in the association.

2. Method

2.1 Location of Conducting, Soil Characteristics, and Experimental Design

The experiments were conducted in a greenhouse at the Universidade Federal da Fronteira Sul (UFFS), Erechim Campus, Rio Grande do Sul, Brazil, located at 27°43'31" S latitude and 52°17'40" W longitude, at an altitude of 650 m. The greenhouse was covered with 150-µm transparent polyethylene film and equipped with a natural ventilation system. The experimental period extended from October to December 2018. Regional climatological

data for this period indicate mean external air temperatures ranging from approximately 18.6 to 21.5 °C and relative humidity between 73 and 77%, with an average of about 8-9 h of sunshine per day. Under greenhouse conditions, air temperature is typically slightly higher than the outside environment; therefore, the internal conditions during the experiment were approximately 24 ± 4 °C (generally ranging from 20 to 30 °C), with relative humidity around 70-80%. Historical climatological data for the region indicate average global solar radiation of approximately 19.5, 22.3, and 22.6 MJ m⁻² day⁻¹ for October, November, and December, respectively. Considering the transmissivity of polyethylene greenhouse covers (generally 70-85%), the radiation inside the greenhouse was estimated to average approximately 14-18 MJ m⁻² day⁻¹ during the experimental period.

The experiments were carried out in plastic pots with a volumetric capacity of 8 dm³ filled with soil classified as a typical Red Aluminoferric Latosol (Streck et al., 2018). According to the soil's physical and chemical analysis, fertilization and pH correction were performed. The soil presented the following characteristics: pH (water) = 4.8; organic matter = 3.5%; P = 4.0 mg dm⁻³; K = 117.0 mg dm⁻³; Al³⁺ = 0.6 cmolc dm⁻³; Ca²⁺ = 4.7 cmolc dm⁻³; Mg²⁺ = 1.8 cmolc dm⁻³; cation exchange capacity (CEC) = 7.4 cmolc dm⁻³; CEC (pH 7.0) = 16.5 cmolc dm⁻³; H⁺Al = 9.7 cmolc dm⁻³; sum of bases (SB) = 6.8 cmolc dm⁻³; base saturation (V) = 41%; and soil texture composed of 60% clay, 15% sand, and 25% silt. Soil moisture was maintained close to field capacity throughout the experiment by periodic irrigation. Water was applied manually whenever necessary, generally at intervals of one to two days depending on evaporative demand, in order to keep the soil near approximately 70-80% of field capacity and avoid water stress.

Both the preliminary experiments and the substitution series experiments were conducted using a randomized block design with four repetitions.

2.2 Installation of Preliminary Experiments in Additive Series

The competitors tested included quinoa genotypes: Q 1303, Q 1324, and Q 1331, in competition with *E. heterophylla* (wild poinsettia) and/or *U. plantaginea* (Alexandergrass). Preliminary experiments were conducted for both quinoa genotypes and *E. heterophylla* and/or *U. plantaginea* monocultures, with the goal of determining the plant density at which final production becomes constant. For this, the following plant densities were used: 1, 2, 4, 8, 16, 24, 32, 40, 48, 56, and 64 plants per pot (equivalent to 25, 49, 98, 196, 392, 587, 784, 980, 1,176, 1,372, and 1,568 plants m⁻²).

Fifty days after the emergence of the species (beginning of the reproductive period), the quinoa, *E. heterophylla* and *U. plantaginea* plants were cut close to the soil to determine the dry matter (DM) of the aerial part. This was quantified by weighing the samples after they were dried in a forced-air oven at 65 ± 5 °C until constant weight was achieved. Based on the average DM values of the species, constant DM production was obtained at a density of 20 plants per pot for all quinoa genotypes, as well as for the populations of *E. heterophylla* and *U. plantaginea* (data not presented).

2.3 Installation of Definitive Experiments in Substitution Series

After identifying the constant final density, six additional experiments were installed to evaluate the competitiveness of the quinoa genotypes Q 1303, Q 1324, and Q 1331 in competition with *E. heterophylla* and/or *U. plantaginea*. All the experiments were conducted in substitution series, with different combinations of the genotypes and weed species, varying the relative proportions (100:0, 75:25, 50:50, 25:75, and 0:100%) or 20:0; 15:5; 10:10; 5:15 and 0:20 plants per pot. To establish the desired densities for each treatment and ensure seedling uniformity, the seeds were previously sown in trays and later transplanted to the pots.

2.4 Variables Evaluated in Quinoa and Weed Plants

Fifty days after emergence (DAE) of the species, the physiological and morphological variables of the quinoa genotypes in competition with the weeds were determined. The physiological variables measured were: chlorophyll index (SPAD), sub-stomatal CO₂ concentration (Ci—μmol mol⁻¹), stomatal conductance of water vapor (GS—mol m⁻² s⁻¹), photosynthetic rate (A—μmol m⁻² s⁻¹), and transpiration rate (E—mol H₂O m⁻² s⁻¹). The carboxylation efficiency (EC—mol CO₂ m⁻² s⁻¹) and water use efficiency (WUE—mol CO₂ mol H₂O⁻¹) were calculated from the ratios of the variables A/Ci and A/E, respectively. The chlorophyll index (CI) was determined using a portable chlorophyll meter (SPAD 502—Plus, Beijing, China) at five points on each plant in the lower, middle, and upper parts. Gas exchange was determined using an infrared gas analyzer (IRGA), model LCA PRO (Analytical Development Co. Ltd., Hoddesdon, UK), which was used on the middle third of the plants in competition. These measurements were made between 08:00 and 11:00 am to maintain uniform environmental conditions during all analyses.

The following morphological variables were measured in the culture plants and weeds: plant height (PH), tillering of *U. plantaginea* or number of leaves of quinoa and *E. heterophylla* (NL), stem/culm diameter (SD), leaf area (LA), and dry matter of the aerial part (DM). The PH was determined by measuring the distance from the soil surface to the tip of the last fully expanded leaf of the species using a ruler graduated in centimeters. The number of tillers or leaves was determined by counting. To determine the LA, an electronic leaf area meter (LICOR-3100) was used, quantifying the variable in all plants for each treatment. After the LA determination, the plants were placed in kraft paper bags and dried in an oven with forced air circulation at 65°C for 48 hours until they reached constant weight to determine the dry matter (DM) of the species.

For nutrient analysis, nitrogen (N) and phosphorus (P), the previously dried leaf samples were ground in a knife mill model Star FT-50 using a mesh sieve with a diameter of 0.5 mm. The foliar nutrients of quinoa were determined following the methodologies proposed by Tedesco et al. (1995).

2.5 Analysis of Substitution Trials

The data analysis was performed using the graphical analysis of variation or productivity method, also known as the conventional method for substitution experiments (Bianchi et al., 2006). This procedure involves creating diagrams based on relative (PR) and total (PRT) productivity or variation. When the PR result is a straight line, it means that the abilities of the species are equivalent. If the PR results in a concave line, it indicates that there is a disadvantage in the growth of one or both species. On the contrary, if the PR shows a convex line, there is a benefit to the growth of one or both species. When the PRT equals 1 (straight line), competition for the same resources occurs; if it is greater than 1 (convex line), competition is avoided; if the PRT is less than 1 (concave line), there is mutual harm to the growth of the species (Rubin et al., 2014).

In addition, the indices of relative competitiveness (CR), relative clustering coefficient (K), and aggressiveness (AG) were determined. The CR represents the comparative growth of quinoa genotypes Q 1303, Q 1331, and Q 1324 (X) in relation to the competitors *E. heterophylla* and/or *U. plantaginea* (Y). K indicates the relative dominance of one species over another, while AG shows which species is more aggressive. Thus, the CR, K, and AG indices point to which species is more competitive, and their joint interpretation provides a more secure understanding of the species' competitiveness (Bianchi et al., 2006; Agostinetto et al., 2013; Rubin et al., 2014).

The statistical analysis procedure for relative productivity or variation included calculating the differences for the PR values (DPR) obtained at the 25%, 50%, and 75% proportions, compared to the values belonging to the hypothetical line at the respective proportions, which were 0.25, 0.50, and 0.75 for PR (Bianchi et al., 2006). The t-test was used to test the differences related to the DPR, PRT, CR, K, and AG indices (Bianchi et al., 2006). The null hypothesis for testing the differences in DPR and AG was that the means were equal to zero ($H_0 = 0$); for PRT and CR, the means were equal to 1 ($H_0 = 1$); and for K, the means of the differences between K_x and K_y were equal to zero [$H_0 = (K_x - K_y) = 0$].

The observed PRT and PR curves were considered different from the expected ones when the expected values (represented by dashed lines) were outside the 95% confidence interval of the observed curves, which were solid and colored with confidence intervals of the same color (Franceschetti et al., 2024). Furthermore, the criterion for considering the PR and PRT curves as different from the hypothetical lines was that, at least in two proportions of the tested competitor species densities, they did not intersect with the colored lines, as adapted from Bianchi et al. (2006).

The results obtained for the morphophysiological variables and foliar nutrients, expressed as mean values per treatment, were subjected to analysis of variance using the F-test. When this indicated significance, the treatment means were compared using the Dunnett test, considering monocultures as controls in these comparisons. A probability of 5% was used for all statistical analyses performed. All statistical analyses were performed using software statistical 'R' (R Core Team, 2014).

3. Results and Discussion

3.1 Competitive Ability of Quinoa Genotypes With *Euphorbia heterophylla* (Wild Poinsettia)

The graphical results indicate that the three quinoa genotypes (Q 1303, Q 1324, and Q 1331) exhibited similar behavior when subjected to competition with *E. heterophylla*, with significant differences in at least two plant proportions for most of the evaluated variables (Figures 1, 2, and 3). In most of the simulations, the total relative productivity (PRT) exhibited values equal to or lower than 1, characterized by predominantly straight or concave characterizing predominantly straight or concave lines, indicating direct competition between the species for the same resources available in the environment, with mutual detriment (Rubin et al., 2014).

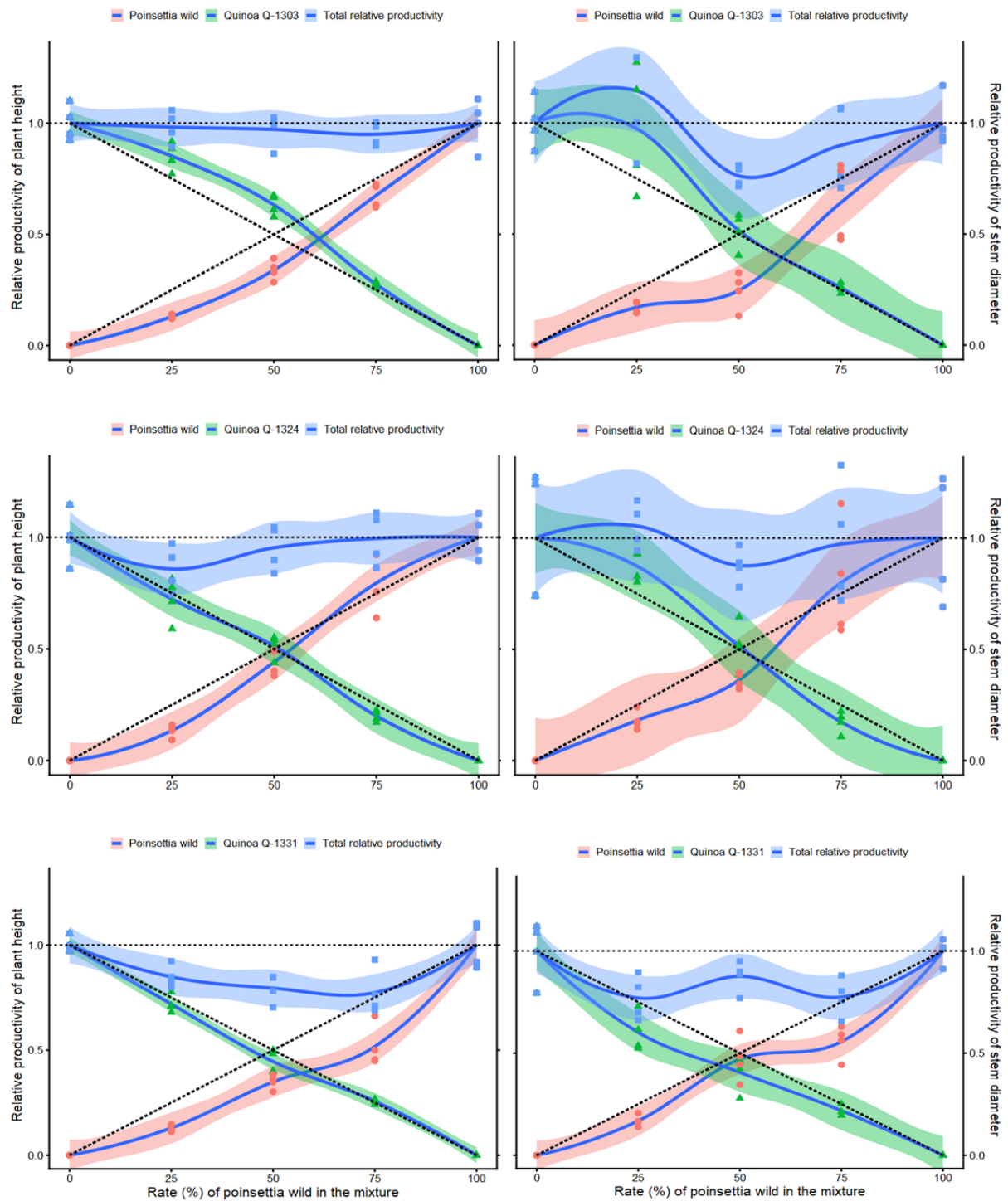


Figure 1. Relative yield (RY) for plant height and stem diameter of quinoa (▲), *Euphorbia heterophylla*—wild poinsettia (●), and total relative yield (TRY) of the community (■), as a function of the proportion of associated plants (quinoa:wild poinsettia). UFFS, Erechim, RS, Brazil. Dashed lines represent the expected values in the absence of competition; solid lines represent the observed values when species competed at different plant proportions; and colored bands represent the standard deviation of the observations

For plant height, it was observed that genotypes Q 1303 and Q 1324 had PRT lines close to the straight line, indicating competition for resources similar to *E. heterophylla*, while genotype Q 1331 had a concave PRT, characterizing mutual detriment to both species (Figure 1). However, the relative productivity (PR) lines showed that, in several proportions, *E. heterophylla* exhibited a more pronounced reduction compared to quinoa,

suggesting a greater sensitivity of the weed to competition, especially in associations involving genotypes Q 1303 and Q 1324. These results may be associated with the etiolation of plants in search of light, as light competition can stimulate an increase in height without necessarily representing greater vigor of the crop (Franco et al., 2017).

For stem diameter, it was observed that the PRT lines were mostly below 1, highlighting that competition negatively affected both species (Figure 1). This behavior can be explained by the plant's strategy to prioritize vertical growth over stem thickening to increase light interception under competitive conditions (Silva et al., 2018).

When analyzing the number of leaves and the chlorophyll index, a reduction was observed in both species, with a predominance of concave PRT lines (Figure 2), demonstrating that interspecific interference was more harmful than intraspecific competition.

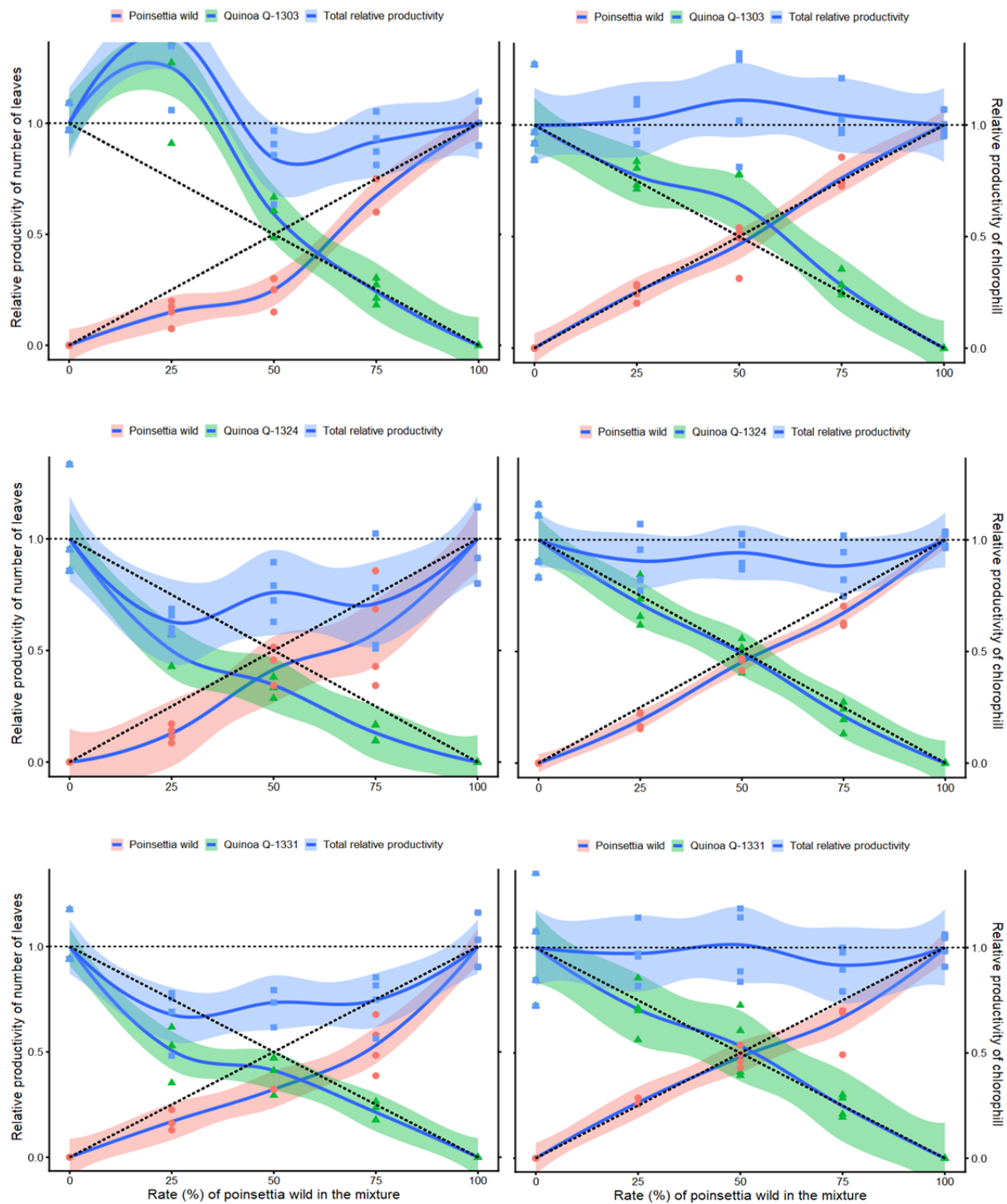


Figure 2. Relative yield (RY) for number of leaves and chlorophyll content of quinoa (▲), *Euphorbia heterophylla*—wild poinsettia (●), and total relative yield (TRY) of the community (■), as a function of the proportion of associated plants (quinoa:wild poinsettia). UFFS, Erechim, RS, Brazil. Dashed lines represent the expected values in the absence of competition; solid lines represent the observed values when species competed at different plant proportions; and colored bands represent the standard deviation of the observations

The data in Table 1 corroborate this trend, showing a significant reduction, particularly at the highest proportions of the competitor. The reduction in the number of leaves resulted in a decrease in leaf area, which, in turn, directly reflected in a reduction in the dry mass of the plants (Figure 3). The PRT lines remained below 1, confirming mutual antagonism between the species in their competition for environmental resources.

Table 1. Morphological responses of quinoa genotypes (*Chenopodium quinoa* Willd.) subjected to interference from *Euphorbia heterophylla* (wild poinsettia), in an experiment conducted under a replacement-series design, evaluated at 50 days after plant emergence. UFFS, Campus Erechim, RS, Brazil

Plant Proportion		Morphological Variables			
Quinoa:Wild Poinsettia	Plant Height (cm)	Stem Diameter (mm)	Number of Leaves	Leaf Area (cm ² pot ⁻¹)	Dry Mass (g pot ⁻¹)
Genotype Q 1303					
100:0 (T)	56.75	3.40	8.25	756.00	19.84
75:25	64.45*	4.42	13.75*	790.84	14.43
50:50	71.80*	3.51	9.75	752.62	22.12
25:75	62.61	3.51	8.00	504.95*	9.98*
CV (%)	7.70	22.30	19.60	21.60	28.30
Wild Poinsettia					
0:100 (T)	69.85	4.35	10.00	2662.31	41.68
25:75	62.80	3.72	9.00	1461.66*	20.82*
50:50	47.40*	2.14*	5.00*	516.06*	5.92*
75:25	36.45*	2.97*	6.00*	480.43*	6.47*
CV (%)	11.80	24.60	21.90	24.80	33.00
Genotype Q 1324					
100:0 (T)	59.15	3.96	10.50	1326.24	19.95
75:25	57.05	4.61	7.00*	1058.17	18.16
50:50	60.60	4.08	7.25*	1199.42	18.39
25:75	47.24*	2.75	5.50*	276.62*	4.70*
CV (%)	13.40	24.40	24.40	24.60	23.80
Wild Poinsettia					
0:100 (T)	60.30	4.20	8.75	2505.69	30.24
25:75	63.98	4.47	6.75	1879.94	25.53
50:50	53.25	3.04	7.25	756.12*	8.67*
75:25	32.55*	3.04	4.50*	378.07*	6.05*
CV (%)	16.50	31.30	30.40	38.60	22.40
Genotype Q 1331					
100:0 (T)	63.32	3.98	8.50	929.04	23.88
75:25	60.70	3.19	5.75	972.41	20.96
50:50	56.43	3.23	7.00	548.22	13.82*
25:75	65.05	3.48	7.25	701.28	14.18*
CV (%)	7.80	17.70	20.50	37.50	22.10
Wild Poinsettia					
0:100 (T)	67.20	3.95	7.75	2536.22	47.88
25:75	46.30*	2.93	5.50*	559.43*	11.01*
50:50	46.90*	3.71	5.00*	508.06*	13.86*
75:25	34.85*	2.66*	5.25*	274.56*	3.37*
CV (%)	15.20	18.30	19.40	39.70	32.10

Note. * Mean differs from the control (T) by Dunnett's test ($p < 0.05$).

The PR of *E. heterophylla*, in general, showed values lower than those of quinoa, indicating that, despite the detriment observed in both species, the weed was more sensitive to the competition exerted by the quinoa genotypes under the evaluated conditions. Thus, although both competitors were negatively affected by cohabitation, it is evident that quinoa exhibited, in certain scenarios, greater tolerance to competition with *E. heterophylla*, particularly genotype Q 1303.

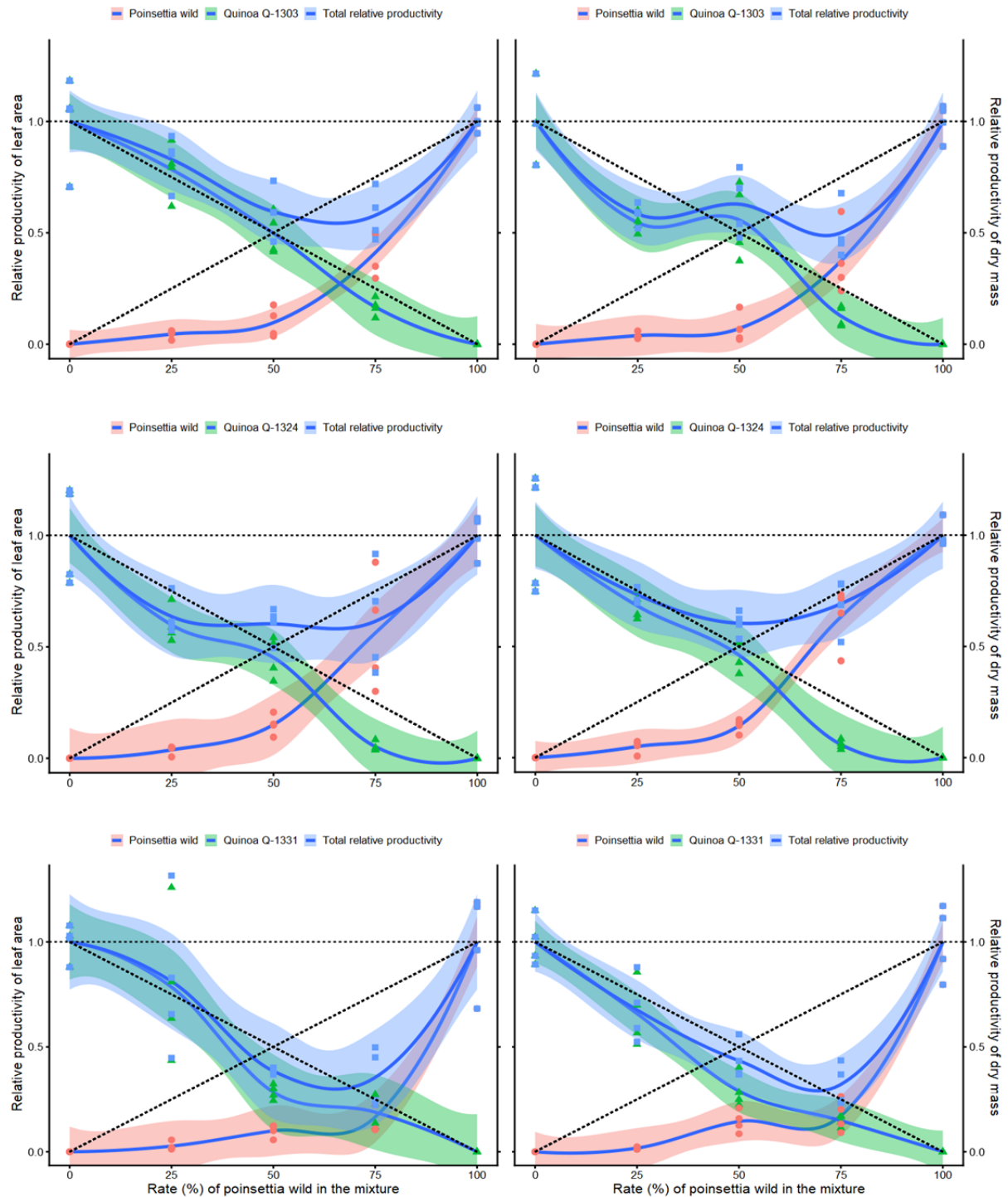


Figure 3. Relative yield (RY) for leaf area and shoot dry mass of quinoa (▲), *Euphorbia heterophylla*—wild poinsettia (●), and total relative yield (TRY) of the community (■), as a function of the proportion of associated plants (quinoa:wild poinsettia). UFFS, Erechim, RS, Brazil. Dashed lines represent the expected values in the absence of competition; solid lines represent the observed values when species competed at different plant proportions; and colored bands represent the standard deviation of the observations

This result is confirmed by the competitiveness indices presented in Table 2. In competition with *E. heterophylla*, the sorghum cultivars BRS 509 and BRS 511 exhibited greater growth compared to the weed, whereas, in competition with *U. plantaginea*, the weed showed greater growth than the crop (Galon et al., 2018). The differential competition of weed species on the crop can be explained by the distinct characteristics of the weed

species. The high degree of interference of *E. heterophylla* with crops is more related to the density and distribution at which it occurs in the fields than its individual ability to compete with crops (Tanveer et al., 2015). On the other hand, Alexandergrass is more adapted to high-temperature and light conditions, producing tillers and having a high competitive capacity with crops due to its rapid growth rate (Velho et al., 2012).

Table 2. Competitiveness indices between quinoa cultivars (*Chenopodium quinoa* Willd.) and *Euphorbia heterophylla* (wild poinsettia), competing at equal plant proportions (50:50), expressed as relative competitiveness (CR), relative crowding coefficients (K), and aggressivity (AG), obtained in experiments conducted under replacement series, at 50 days after plant emergence. UFFS, Erechim, RS, Brazil

Variables	CR ²	Kx ³ _(quinoa)	Ky _(wild poinsettia)	AG ⁴
<i>Plant Height</i>				
Q 1303	1.884±0.111*	1.753±0.169*	0.519±0.051	0.293±0.026*
Q 1324	1.169±0.066	1.066±0.101	0.806±0.096	0.071±0.023
Q 1331	1.284±0.087*	0.817±0.089*	0.539±0.091	0.097±0.030
<i>Stem Diameter</i>				
Q 1303	2.559±0.704	1.108±0.163*	0.037±0.07	0.271±0.079*
Q 1324	1.452±0.215	1.144±0.251	0.57±0.042	0.153±0.069
Q 1331	0.917±0.163	0.706±0.111	0.954±0.216	-0.065±0.090
<i>Number of Leaves</i>				
Q 13 03	2.475±0.266*	1.505±0.217*	0.342±0.059	-0.158±0.064
Q 13 24	0.854±0.089	0.533±0.052	0.736±0.131	-0.069±0.040
Q 13 31	1.276±0.129	0.724±0.112	0.476±0.059	0.089±0.042
<i>Chlorophyll Index</i>				
Q 1303	1.404±0.117*	2.289±0.714	0.917±0.159	0.341±0.013*
Q 1324	1.087±0.074	0.985±0.123	0.828±0.041	0.038±0.034
Q 1331	1.113±0.170	1.382±0.471	0.936±0.089	0.053±0.079
<i>Leaf Area</i>				
Q 1303	7.573±2.372	1.046±0.198*	0.112±0.042	0.401±0.059*
Q 1324	3.340±0.842	0.864±0.154*	0.180±0.032	0.301±0.062*
Q 1331	3.226±0.849	0.400±0.034*	0.112±0.019	0.184±0.032*
<i>Dry Mass</i>				
Q 1303	14.243±4.796	1.538±0.492	0.081±0.041	0.487±0.106*
Q 1324	3.406±0.633*	0.878±0.120*	0.168±0.020	0.318±0.047*
Q 1331	2.222±0.468	0.422±0.086	0.172±0.036	0.145±0.050

Note. ¹ Measurement of the evaluated variable at the indicated competition level and differences relative to the control, compared by Dunnett's test; ² significant when different from 1 by the t-test; ³ difference between Kx and Ky, at the same competition levels, compared by the t-test using Welch's criterion; ⁴ significant when different from 0 by the t-test; * significant difference at $p < 0.05$.

3.2 Competitive Ability of Quinoa Genotypes With *Urochloa plantaginea* (Alexandergrass)

The three quinoa genotypes (Q 1303, Q 1324, and Q 1331) exhibited similar behavior when subjected to competition with *U. plantaginea* (Alexandergrass), with significant differences in the variables plant height, stem diameter, number of leaves/tillers, leaf area, chlorophyll and dry mass in at least two plant proportions evaluated (Figures 4, 5, and 6). Upon analyzing the total relative productivity (PRT), it was observed that concave lines or values below 1 predominated for most of the variables, indicating mutual detriment between quinoa and Alexandergrass. This fact characterizes direct competition for the same environmental resources, mainly those related to water, light, and nutrients, between the crop and the weed, as also reported by Rubin et al. (2014).

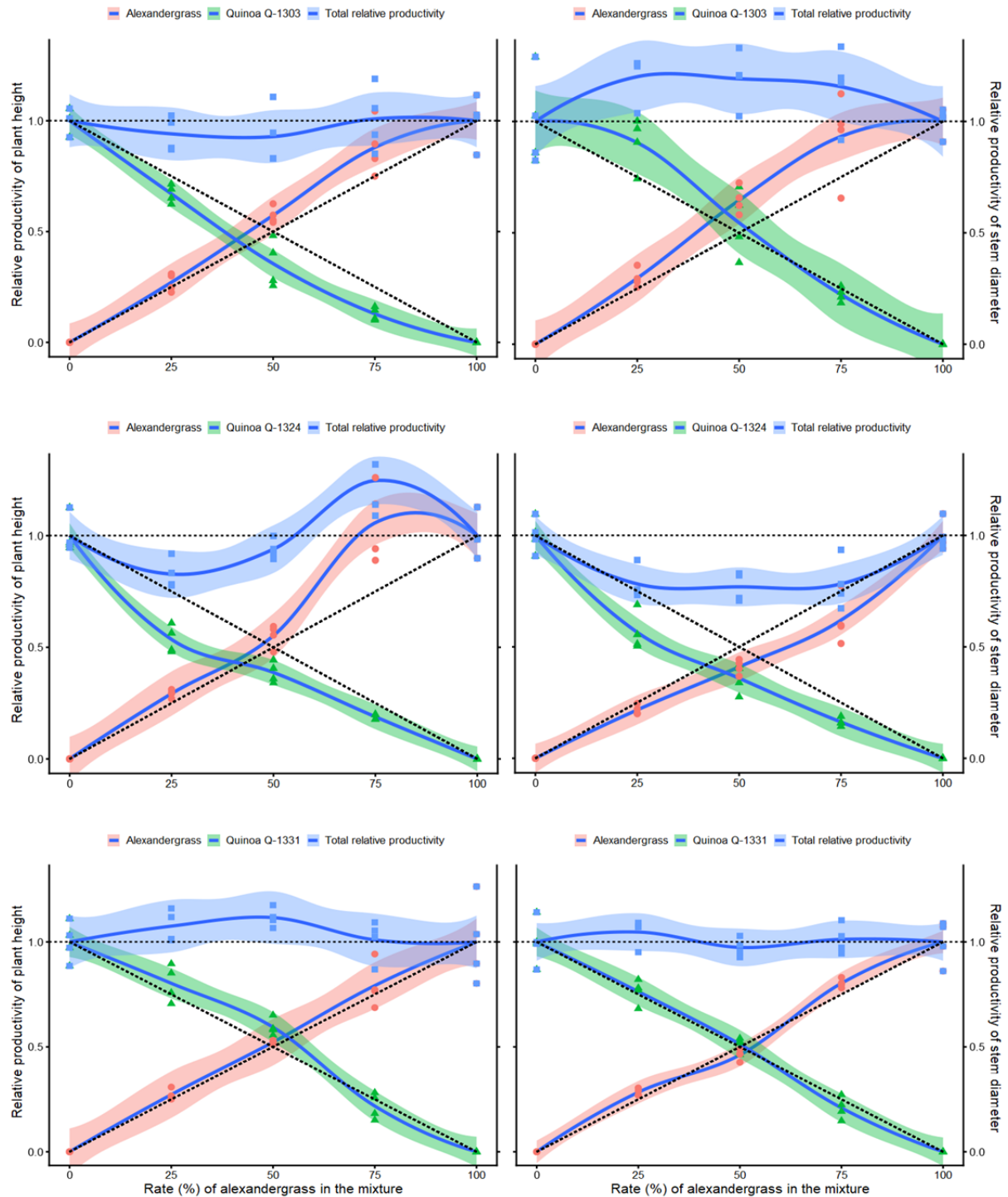


Figure 4. Relative yield (RY) for plant height and stem diameter of quinoa (▲), *Urochloa plantaginea*—Alexandergrass (●), and total relative yield (TRY) of the community (■), as a function of the proportion of associated plants (quinoa:Alexandergrass). UFFS, Erechim, RS, Brazil. Dashed lines represent the expected values in the absence of competition; solid lines represent the observed values when species competed at different plant proportions; and colored bands represent the standard deviation of the observations

For plant height, the PRs indicated that Alexandergrass generally exhibited greater growth capacity compared to quinoa, especially at the higher proportions of weed plants in the association (Figure 4). The PRT showed a behavior close to a straight line for some genotypes (Q 1303) and concave for others (Q 1324 and Q 1331), confirming that competition negatively affected both species, but with a greater detriment to quinoa at certain

proportions. Galon et al. (2025) also observed substantial damage to quinoa crops when infested by *Lolium multiflorum* (ryegrass) and *Raphanus raphanistrum* (radish), which corroborates the results found in this study.

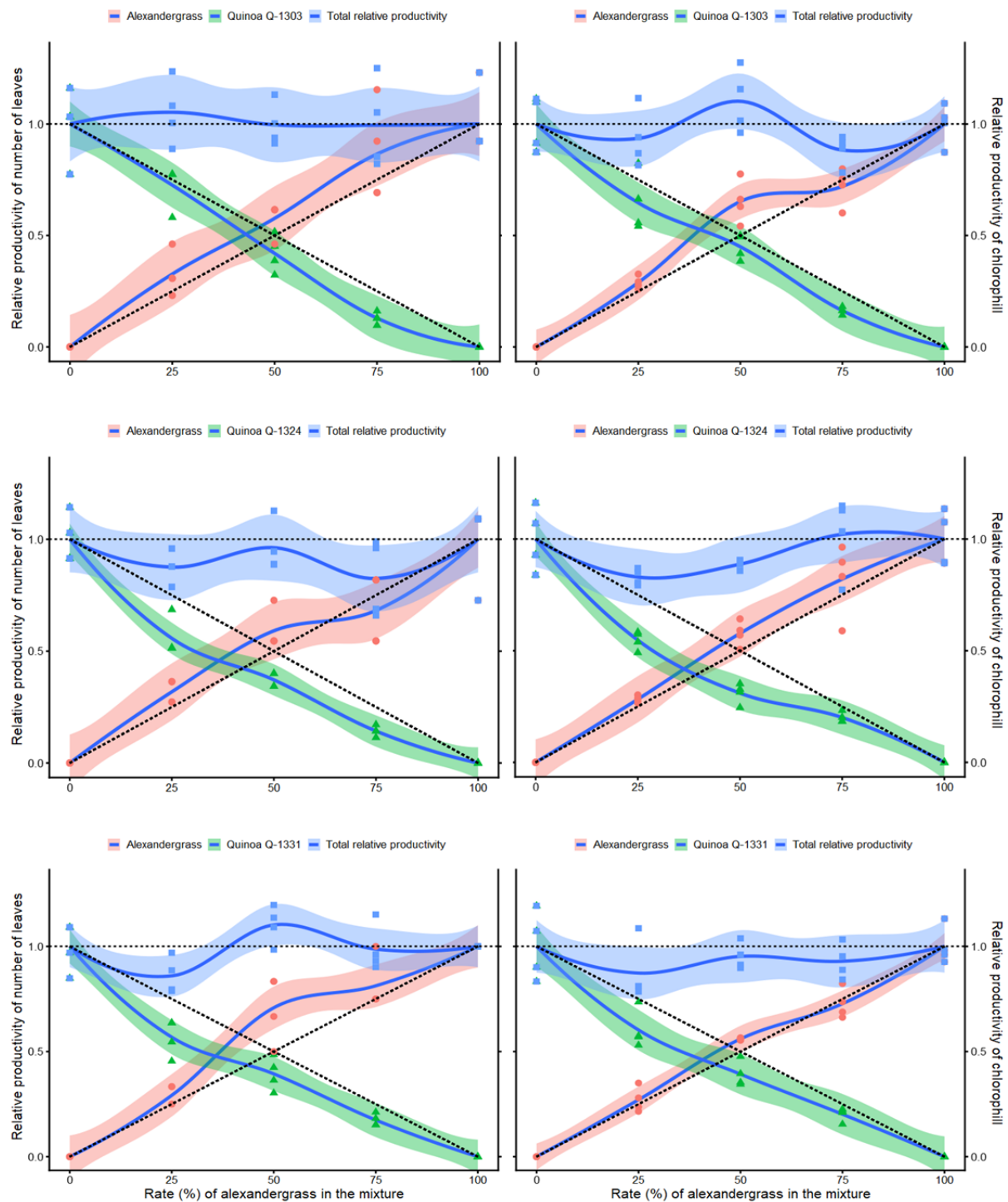


Figure 5. Relative yield (RY) for number of leaves and chlorophyll content of quinoa (▲), *Urochloa plantaginea*—Alexandergrass (●), and total relative yield (TRY) of the community (■), as a function of the proportion of associated plants (quinoa:Alexandergrass). UFFS, Erechim, RS, Brazil. Dashed lines represent the expected values in the absence of competition; solid lines represent the observed values when species competed at different plant proportions; and colored bands represent the standard deviation of the observations

This increase in height observed in Alexandergrass can be explained by its adaptive strategy of faster growth under interspecific competition, favoring light interception and overshadowing the crop. Several studies have reported that species with higher competitive ability tend to exhibit rapid internode elongation and canopy expansion, contributing to greater solar radiation interception capacity (Galon et al., 2018; Pierik & Ballaré, 2021).

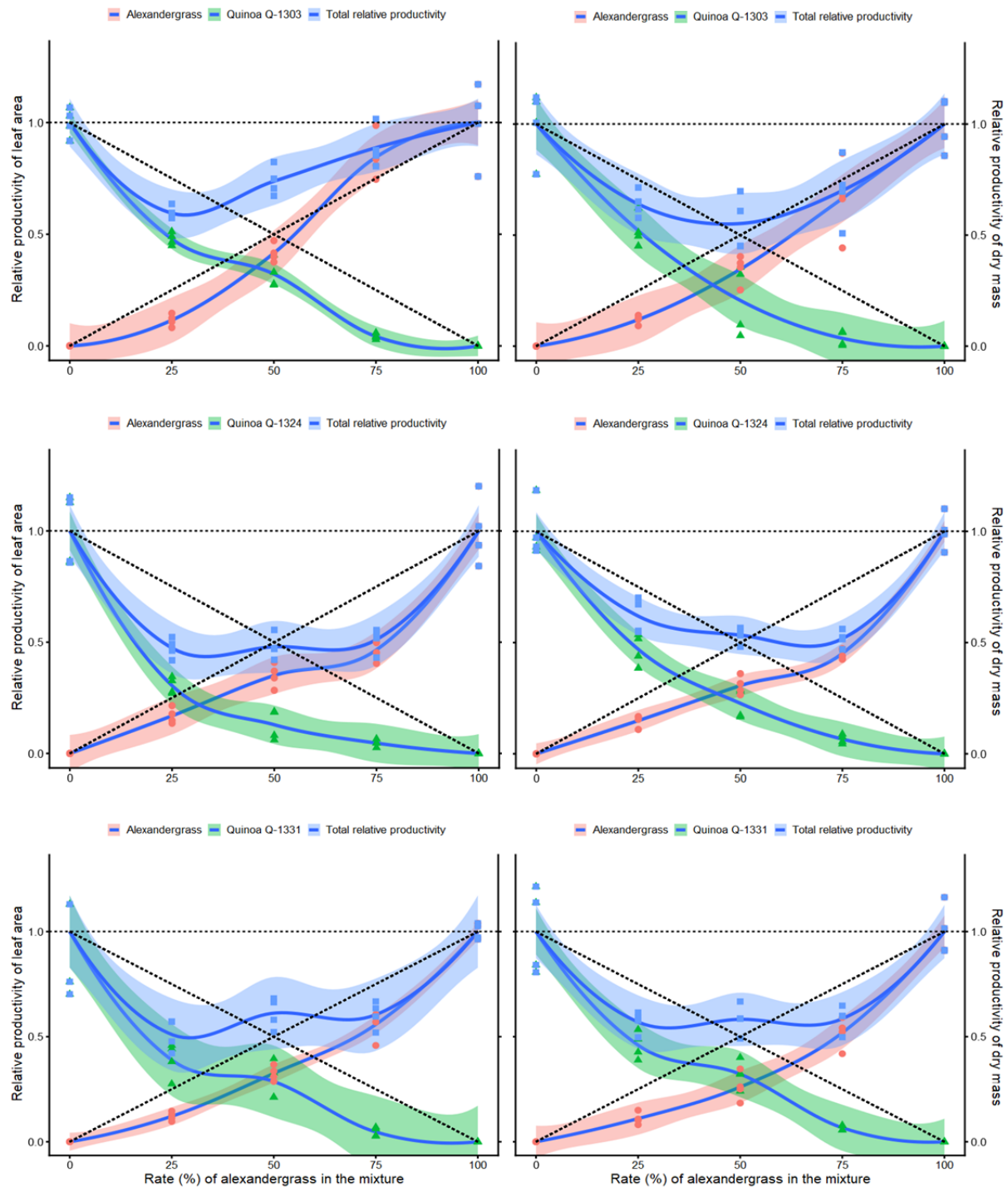


Figure 6. Relative yield (RY) for leaf area and shoot dry mass of quinoa (▲), *Urochloa plantaginea*—Alexandergrass (●), and total relative yield (TRY) of the community (■), as a function of the proportion of associated plants (quinoa:Alexandergrass). UFFS, Erechim, RS, Brazil. Dashed lines represent the expected values in the absence of competition; solid lines represent the observed values when species competed at different plant proportions; and colored bands represent the standard deviation of the observations

Regarding stem/tiller diameter, the PRT lines were predominantly below 1, indicating losses for both species (Figure 4). This behavior suggests that, under competition, plants tend to prioritize vertical growth over stem thickening, resulting in a reduction in diameter as a consequence of resource limitation, especially photoassimilates (Balbinot et al., 2016; Pierik & Ballaré, 2021).

For the number of leaves (quinoa) and tillers (Alexandergrass), it was observed that, in general, quinoa exhibited a reduction in development at all proportions of the association, while Alexandergrass showed, in some scenarios, less relative impact (Figure 5). The total relative productivity lines remained close to or below 1, indicating mutual detriment in the plant community, with direct competition between the species for the same resources. This pattern shows that interspecific interference was more harmful than intraspecific interference, which corroborates the work of Galon et al. (2025) when studying the effect of ryegrass and radish on quinoa genotypes.

Leaf area and dry mass of the aerial part exhibited similar behavior, with a marked reduction as the proportion of Alexandergrass in the associations with quinoa genotypes increased (Figure 6; Tables 3 and 4). The PRs for quinoa were mostly lower than expected, and the PRTs remained below 1, confirming intense interspecific competition. This behavior reinforces that the presence of Alexandergrass significantly hampers the vegetative growth of quinoa, directly affecting the photosynthetic capacity of the plants. The reduction in leaf area limits light interception and, consequently, photoassimilate production, which negatively impacts biomass accumulation. Similar results were observed by Rubin et al. (2014), who reported that PRT values lower than 1 indicate mutual antagonism between the species involved in competition.

Table 3. Morphological responses of quinoa genotypes (*Chenopodium quinoa* Willd.) subjected to interference from *Urochloa plantaginea* (Alexandergrass), in an experiment conducted under a replacement-series design, evaluated at 50 days after plant emergence. UFFS, Erechim, RS, Brazil

Plant Proportion	Morphological Variables				
Quinoa:Alexandergrass	Plant Height (cm)	Stem Diameter (mm)	Number of Leaves	Leaf Area (cm ² pot ⁻¹)	Dry Mass (g pot ⁻¹)
Genotype Q 1303					
100:0 (T)	66.35	2.84	7.75	1051.85	21.04
75:25	59.30	3.42	7.50	671.82*	14.59
50:50	47.15*	3.09	6.50	677.09*	8.65*
25:75	34.17*	2.53	4.00*	177.84*	2.97*
CV (%)	18.30	22.40	19.30	14.10	38.50
Alexandergrass					
0:100 (T)	52.60	3.20	3.25	2806.25	59.35
25:75	61.70	3.98	3.75	3161.80	52.65
50:50	60.30	4.14*	3.75	2331.56	41.11*
75:25	59.95	3.80	4.25	1293.63*	28.45*
CV (%)	13.60	16.20	25.80	17.00	22.20
Genotype Q 1324					
100:0 (T)	63.60	4.24	8.75	1425.23	16.55
75:25	45.39*	3.20*	6.50*	578.93*	10.36*
50:50	49.27*	3.05*	6.50*	367.42*	7.51*
25:75	48.00*	2.76*	5.00*	263.97*	4.37*
CV (%)	10.80	14.70	14.30	27.20	21.00
Alexandergrass					
0:100 (T)	49.41	4.05	2.75	3747.53	53.15
25:75	69.70*	3.34*	2.50	2326.76*	31.98*
50:50	54.55	3.32*	3.25	2627.30*	32.58*
75:25	57.80	3.52	3.50	2533.63*	31.73*
CV (%)	13.30	12.30	20.10	18.00	12.90
Genotype Q 1331					
100:0 (T)	57.60	3.66	8.25	1244.68	23.06
75:25	61.65	3.73	6.25*	645.91*	14.13*
50:50	68.40	3.75	6.50	713.85*	14.85*
25:75	50.23	3.06	5.75*	232.18*	6.15*
CV (%)	16.20	15.00	17.60	39.50	23.40
Alexandergrass					
0:100 (T)	52.85	3.56	3.00	4324.35	61.47
25:75	55.80	3.82	3.25	3217.13*	42.51*
50:50	55.20	3.29	4.25*	2812.96*	32.04*
75:25	57.60	4.04*	3.50	2097.61*	27.10*
CV (%)	14.20	7.50	19.60	11.50	19.70

Note. * Mean differs from the control (T) by Dunnett's test ($p \leq 0.05$).

The joint analysis of Figures 4, 5, and 6, the morphological variables (Table 3), and the competitiveness indices (Table 4) highlights that, in general, Alexandergrass exhibits greater competitive ability than quinoa, especially at higher proportions of the weed in the association. However, among the quinoa genotypes, it was observed that Q 1303 showed slightly higher tolerance to competition when compared to Q 1324 and Q 1331, which exhibited more pronounced reductions in their growth variables.

Table 4. Competitiveness indices between quinoa cultivars (*Chenopodium quinoa* Willd.) and *Urochloa plantaginea* (Alexandergrass), competing at equal plant proportions (50:50), expressed as relative competitiveness (CR), relative crowding coefficients (K), and aggressivity (A), obtained in experiments conducted under replacement series, at 50 days after plant emergence. UFFS, Erechim, RS, Brazil

Variables	CR ²	Kx ³ _(quinoa)	Ky _(Alexandergrass)	AG ⁴
Plant Height				
Q 1303 × Alexandergrass	0.617±0.083*	0.585±0.137*	1.357± 0,11	-0.218±0.046*
Q 1324 × Alexandergrass	0.710±0.073*	0.639±0.063*	1.253±0,119	-0.165±0.043*
Q 1331 × Alexandergrass	1.137±0.036*	1.481±0.133	1.094±0,019	0.072±0.019*
Stem Diameter				
Q 1303 × Alexandergrass	0.858±0.144	1.395±0.406	1.896±0.267	-0.101±0.096
Q 1324 × Alexandergrass	0.882±0.090	0.572±0.078	0.699±0.046	-0.051±0.040
Q 1331 × Alexandergrass	1.113±0.049	1.058±0.068	0.860±0.043	0.051±0.021
Number of Leaves				
Q 1303 × Alexandergrass	0.743±0.102	0.749±0.127*	1.414±0.186	-0.158±0.064
Q 1324 × Alexandergrass	0.635±0.038*	0.594±0.042	1.567±0.367	-0.219±0.038
Q 1331 × Alexandergrass	0.602±0.136	0.671±0.109	3.250±1.031	-0.314±0.117
Chlorophyll Index				
Q 1303 × Alexandergrass	0.694±0.039*	0.831±0.093	2.076±0.488	-0.203±0.035*
Q 1324 × Alexandergrass	0.546±0.065*	0.454±0.047*	1.398±0.160	-0.267±0.050*
Q 1331 × Alexandergrass	0.700±0.052*	0.659±0.088*	1.273±0.014	-0.168±0.029*
Leaf Area				
Q 1303 × Alexandergrass	0.783± 0.089	0.485± 0.073*	0.717± 0.062	-0.094± 0.042
Q 1324 × Alexandergrass	0.388±0.118*	0.153±0.044*	0.547±0.062	-0.222±0.054*
Q 1331 × Alexandergrass	0.903±0.179	0.420±0.093	0.485±0.038	-0.038±0.058
Dry Mass				
Q 1303 × Alexandergrass	0.665±0.295	0.297±0.128	0.541±0.072	-0.141±0.103
Q 1324 × Alexandergrass	0.769±0.156	0.301±0.056	0.446±0.044	-0.080±0.052
Q 1331 × Alexandergrass	1.327±0.293	0.485±0.072	0.361±0.063	0.061±0.055

Note. ¹ Measurement of the evaluated variable at the indicated competition level and differences relative to the control, compared by Dunnett's test; ² significant when different from 1 by the t-test; ³ difference between Kx and Ky, at the same competition levels, compared by the t-test using Welch's criterion; ⁴ significant when different from 0 by the t-test. * significant difference at $p < 0.05$.

These results confirm that Alexandergrass is a species that easily adapts to different environments and has a high competitive ability when infesting various agricultural crops, especially maize, beans, and soybeans. This is due to its higher efficiency in exploiting environmental resources (Skóra Neto, 2001; Vidal et al., 2010; Dias et al., 2013). Moreover, its high seed production, persistence in the soil seed bank, large tiller production, rapid growth rate, and C₄ metabolism, which demonstrates high efficiency in resource utilization, reinforce its importance as a difficult-to-manage weed when it infests crops (Voll et al., 2001; Velho et al., 2012; Bastiani et al., 2016; Ferreira et al., 2021).

3.3 Effect on the Physiological Variables of Quinoa Genotypes in Competition With *Urochloa plantaginea* (Alexandergrass) and *Euphorbia heterophylla* (Wild Poinsettia)

The physiological performance of quinoa depended on the weed species, with the interspecific competition affecting gas exchange and photosynthetic efficiency. In general, increasing in weed proportion promoted detrimental effects on the physiological variables (Table 5). In competition with Alexandergrass, genotype Q1303 was greatly affected as weed proportion increased. There was increased substomatal CO₂ concentration (Ci), as well as reductions in chlorophyll content, photosynthetic rate (A), carboxylation efficiency (EC), and water use efficiency (EUA), most probably due to the non-stomatal limitation to carbon assimilation. Alexandergrass, thus, exerts strong competitive pressure on quinoa, likely due to rapid growth and efficient capture of environmental resources.

Table 5. Differences between plants associated or not with quinoa (*Chenopodium quinoa* Willd.) genotypes in competition with *Euphorbia heterophylla* (wild poinsettia) and/or *Urochloa plantaginea* (Alexandergrass) for crop physiological variables: chlorophyll content (SPAD), substomatal CO₂ concentration (C_i— $\mu\text{mol mol}^{-1}$), stomatal conductance to water vapor (G_s— $\text{mol m}^{-2} \text{s}^{-1}$), transpiration rate (E— $\text{mol H}_2\text{O m}^{-2} \text{s}^{-1}$), photosynthetic rate (A— $\mu\text{mol m}^{-2} \text{s}^{-1}$), carboxylation efficiency (CE— $\text{mol CO}_2 \text{m}^{-2} \text{s}^{-1}$), and water use efficiency (WUE— $\text{mol CO}_2 \text{mol H}_2\text{O}^{-1}$). UFFS, Campus Erechim, RS, Brazil

Plant proportion Quinoa:Competitors	Physiological Variables of Quinoa in Competition With Weeds						
	Chlorophyll	C _i	GS	E	A	EC	EUA
Genotype Q 1303 × Alexandergrass							
100:0	7.28	187.78	0.62	3.78	38.48	0.21	10.35
75:25	6.28	208.89	0.66	4.05	34.17	0.17	8.41
50:50	6.54	339.78*	0.61	3.50	27.75	0.08*	7.92
25:75	4.75*	326.25*	0.69	3.82	13.63*	0.05*	3.61*
CV (%)	16.40	16.13	22.93	15.03	36.37	42.28	36.33
Genotype Q 1324 × Alexandergrass							
100:0	8.48	345.89	0.70	6.00	12.39	0.04	2.23
75:25	6.19*	336.44	0.97	5.88	14.50	0.04	2.52
50:50	5.26*	331.92	1.36*	6.12	13.51	0.04	2.33
25:75	6.82*	316.75*	1.30*	6.75	16.31	0.05*	2.52
CV (%)	14.13	4.15	18.93	22.17	14.71	16.70	31.32
Genotype Q 1331 × Alexandergrass							
100:0	6.50	322.92	1.85	7.99	16.57	0.05	2.00
75:25	5.22	321.83	1.14	7.43	17.39	0.05	2.34
50:50	5.11	338.88	3.26*	12.05*	11.35	0.03	0.98
25:75	5.25	323.58	3.23*	12.90*	16.31	0.05	1.27
CV (%)	17.70	5.81	28.42	13.68	47.38	47.66	45.39
Genotype Q 1303 × Wild Poinsettia							
100:0	8.37	243.89	0.68	3.81	31.71	0.13	8.39
75:25	8.62	235.11	0.50	3.88	35.66	0.15	9.29
50:50	10.81	232.33	0.44*	3.83	39.26*	0.17*	10.31
25:75	9.46	235.89	0.68	4.07	39.40*	0.17*	9.69
CV (%)	21.30	9.59	19.44	10.55	8.77	9.39	11.54
Genotype Q 1324 × Wild Poinsettia							
100:0	8.49	339.50	1.06	6.59	14.29	0.04	2.21
75:25	8.08	331.00	0.82	6.79	17.02	0.05	2.58
50:50	8.33	325.67	1.06	6.56	15.58	0.05	2.38
25:75	7.14	333.00	1.34	6.74	16.47	0.05	2.99
CV (%)	20.60	7.67	18.53	22.52	11.03	14.66	21.27
Genotype Q 1331 × Wild Poinsettia							
100:0	7.71	324.11	1.53	9.65	23.77	0.07	2.46
75:25	7.28	321.00	0.92	7.34	19.67	0.06	3.84
50:50	8.22	274.00*	1.14	7.83	17.76	0.07	2.27
25:75	7.64	338.94	1.54	6.80	18.44	0.05	2.76
CV (%)	28.10	7.35	35.16	19.54	17.77	17.41	26.78

Note. * Mean differs from the control (T) by Dunnett's test ($p \leq 0.05$).

Genotype Q1324 had a different behavior when associated with Alexandergrass. Although chlorophyll levels were reduced in mixed stands, stomatal conductance (GS) increased with increasing weed proportion, while A remained relatively stable (Table 5). This behavior suggests a compensatory physiological adjustment aiming to maintain carbon assimilation in the presence of the competitor. For genotype Q1331, competition with Alexandergrass resulted in marked increases in GS and transpiration rate (E) at higher weed proportions, but

without proportional gains in A. This pattern indicates lower efficiency in carbon assimilation relative to water loss (Table 5) and these responses are usually reported when plants experience resource limitation or shading (Pierik & Ballaré, 2021; Tang et al., 2025).

When quinoa competed with wild poinsettia, the physiological responses were generally less pronounced (Table 5). For genotype Q1303, increases in A and EC were observed at intermediate and high weed proportions. Genotypes Q1324 and Q1331 also showed relatively small physiological variations when competing with wild poinsettia, indicating greater stability of gas exchange parameters across plant proportions. Overall, these results suggest that the competitive ability of wild poinsettia over quinoa is lower than that of Alexandergrass, particularly regarding effects on physiological processes related to carbon assimilation. From a competition ecology perspective, grasses such as Alexandergrass tend to be strong competitors due to rapid early growth and efficient exploitation of environmental resources (Savić et al., 2025), posing stronger physiological limitations for neighboring crop plants.

3.4 Nitrogen (N) and Phosphorus (P) Concentrations of Quinoa Genotypes in Competition With *Urochloa plantaginea* (Alexandergrass) and *Euphorbia heterophylla* (Wild Poinsettia)

For the competition between quinoa and *U. plantaginea* (Table 6), it was observed that the genotype Q 1303 showed a significant increase in nitrogen (N) content when subjected to infestation at the 75:25 (quinoa: Alexandergrass) proportion. In contrast, the genotypes Q 1324 and Q 1331 generally exhibited less pronounced variations or modest reductions in the other proportions evaluated. Regarding phosphorus (P) concentration, the changes were isolated and less consistent, although the genotype Q 1331 showed significant differences in some proportions during competition, indicating a differential response among the evaluated genetic materials (Table 6).

When in competition with *E. heterophylla*, a significant reduction in N content was observed in the genotypes Q 1303 and Q 1324 at the 50:50 and 25:75 (quinoa: wild poinsettia) proportions compared to monoculture (100:0). The genotype Q 1331 also showed a reduction in N content at the highest proportion of competition with the weed (Table 6). In contrast, P concentrations showed less variability, with few statistical differences between the proportions, suggesting that the absorption of this nutrient was less sensitive to interspecific interference under the experimental conditions.

These results indicate that competition with weeds, especially at higher plant proportions, may compromise the absorption of essential nutrients, particularly nitrogen, an element directly related to vegetative growth and the synthesis of structural compounds and chlorophyll. However, the magnitude of these changes varied according to the genotype evaluated, showing that there is genetic variability in nutrient absorption efficiency and utilization under competitive stress conditions. Quinoa is recognized for its tolerance to adverse environments and its ability to grow in low-fertility soils or under stress conditions (Jiang et al., 2022). Thus, the observed changes in foliar N and P concentrations demonstrate that, although the crop shows resilience, the interference of competitive weed species can negatively affect its nutritional status and, consequently, its morphophysiological performance.

Table 6. Responses of quinoa (*Chenopodium quinoa* Willd.) genotypes to interference from *Urochloa plantaginea* (Alexandergrass) and/or *Euphorbia heterophylla* (wild poinsettia), expressed as nutrient contents: nitrogen—N (dag kg⁻¹, %) and phosphorus—P (dag kg⁻¹, %) of plants grown in replacement-series experiments. UFFS, Campus Erechim, RS, Brazil

Plant Proportion Quinoa:Competitors	Nutrients in Quinoa Genotypes Competing With Weeds					
	Q 1303 × Alexandergrass		Q 1324 × Alexandergrass		Q 1331 × Alexandergrass	
	N	P	N	P	N	P
100:0	7.60	0.84	6.15	0.83	9.89	1.00
75:25	10.00*	0.85	5.59	0.72	8.66	0.80*
50:50	7.31	0.83	5.28	0.80	8.19	0.75*
25:75	6.97	0.87	6.62	0.79	8.69	0.74*
CV (%)	13.19	11.62	15.40	8.05	8.70	7.11
Plant proportion Quinoa:Competitors	Q 1303 × Wild Poinsettia		Q 1324 × Wild Poinsettia		Q 1331 × Wild Poinsettia	
	N	P	N	P	N	P
	N	P	N	P	N	P
100:0	6.29	1.15	10.15	1.14	7.64	1.22
75:25	5.71	1.11	9.11*	1.24	9.43*	1.23
50:50	5.25*	1.11	8.43*	1.22	7.45	1.18
25:75	7.07*	1.15	8.71*	1.19	6.02*	1.11
CV (%)	5.55	9.37	5.54	6.68	2.14	8.53

Note. * Mean differs from the control (T) by Dunnett's test ($p \leq 0.05$).

3.5. General Synthesis of Competition (*Quinoa* × *Euphorbia heterophylla* × *Urochloa plantaginea*)

In most of the evaluated variables, the total relative productivity (PRT) values were either lower than or close to 1, with a predominance of concave or straight lines, indicating competition for the same environmental resources and mutual harm between the species involved. This pattern is typical of systems where competing plants exploit similar ecological niches, intensifying the competition for light, water, and nutrients (Bianchi et al., 2006; Rubin et al., 2014; Galon et al., 2025).

Among the two weed species evaluated, *U. plantaginea* was more aggressive toward quinoa, causing greater reductions in leaf area, dry biomass, and the number of vegetative structures, particularly at higher weed infestation proportions. This behavior highlights its strong competitive capacity, attributed to its rapid initial growth, high biomass accumulation, and C₄ photosynthetic metabolism—traits that give the weed an advantage in competitive environments (Voll et al., 2001; Vidal et al., 2010; Dias et al., 2013).

However, it was observed that some quinoa genotypes, especially Q 1303, exhibited greater relative tolerance to interference, showing less reduction in certain variables and better performance in some competitiveness indices. This behavior reinforces the importance of selecting more adapted and competitive genotypes as a complementary strategy for integrated weed management.

Overall, the results confirm that interspecific competition causes greater damage to the morphophysiological variables of both the crop and the weed species when compared to intraspecific competition. These findings align with studies on other crops, such as rice, soybeans, maize, and beans, where the presence of weeds resulted in significant reductions in the growth and development of cultivated plants (Vidal et al., 2010; Velho et al., 2012; Araújo et al., 2018; Galon et al., 2025).

Overall, the results demonstrate that the competitive outcome between quinoa and weeds depended on both the weed species and the genotype. *Urochloa plantaginea* showed greater competitive ability than *Euphorbia heterophylla*, particularly at higher weed proportions. Among the quinoa genotypes, Q 1303 consistently showed greater tolerance to interference, presenting smaller reductions in growth, better performance in several competitiveness indices, and more stable physiological responses compared with Q 1324 and Q 1331. In contrast, genotype Q 1331 exhibited greater physiological imbalance under competition with Alexandergrass and did not maintain the same level of stability in growth variables. Therefore, genotype Q 1303 proved to be the most competitive and best adapted to coexist with the studied weed species.

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