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EVALUATING MAIZE-LEGUME-CUCURBIT INTERCROPPING FOR ENHANCING DROUGHT RESILIENT SMALLHOLDER AGRICULTURAL SYSTEMS OF CENTRAL CHILE

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ABSTRACT
Drought stress is one of the most limiting factors, mainly in Mediterranean and arid or semi-arid environments worldwide. This situation is not an exception in central Chile, where a decline in rainfall of approximately 25% to 45% has been recorded over the past few decades, affecting mostly family farm agriculture. The main objective of the present study was to assess the intercropping of legume and cucurbits with maize, as a starting point to determine the best combinations. The experiment was conducted under greenhouse conditions in a bifactorial arrangement based on a completely randomized design with three replications. The treatments included 13 cropping systems: (T1-maize, T2-common bean, T3-chickpea, T4-pumpkin and T5-cucumber, as sole crops; T6-maize and common bean, T7-maize and chickpea, T8-maize and pumpkin, T9-maize and cucumber, T10-maize, common bean and pumpkin, T11-maize, common bean and cucumber, T12-maize, chickpea and pumpkin, and T13-maize, chickpea and cucumber); and two irrigation levels (40% and 100% of water holding capacity (WHC) of substrate, named as R100 and R40, respectively). The results showed that intercropping system and irrigation level altered morphological and physiological parameters. The water deprivation decreased significantly root and shoot biomass, height and relative growth rate of all the crops. Moreover, the results showed that intercropping enhanced land use productivity, with a land equivalent ratio (LER) with a median of 1.30. Overall, the results of the current study indicated that intercropping of maize, common beans and pumpkin could aid smallholder farmers to cope with water shortage, particularly in Mediterranean and other arid and semi-arid environments.
Keywords: drought, intercropping, Mediterranean environments.

INTRODUCTION

Global warming has led to a temperature increase of around 1.5 to 2º C (Tereucán et al. 2021), which can lead to various negative hydrological, ecological and socio-economic consequences. Drought has altered the rainfall patterns, increasing the frequency, severity, and duration (Ahumada et al. 2023). Currently, at least 70% of available water is consumed for irrigation and other agricultural purposes worldwide (Qadari et al. 2023), increasing the pressure for water availability. Given the increasing rainfall shortages, especially in Mediterranean and other dry regions (Peña-Guerrero et al., 2019), it is urgent to improve water use and adopt farming strategies that support current and future food production. In Chile, agriculture accounts for 73% of total water use (Raggio Carvallo & Herrera González, 2020). Droughts have become increasingly common in recent years due to low rainfall and competing water demands, especially in central Chile, a key agricultural region (Kremer et al., 2020). This area is largely dominated by family farming, which faces challenges such as limited human capital and poor access to markets and services (Jara-Rojas et al., 2020). According to Fernández et al. (2023), drought problems in central Chile increased, due to rainfall drop, from 25 to 45% in the decade of 2010 to 2020. This situation will strongly affect Chilean agricultural productivity due to a high variability in the amount and distribution of rainfall during the growing season, which represents a major limiting factor (Ashwin et al. 2023; Chieb & Gachomo, 2023; Silva et al. 2023). Therefore, to develop or adopt sustainable and ecological-friendly management strategies that can be applied for family farm producers in central Chile is mandatory.

Various alternatives to address this concern have been developed worldwide. These include breeding, the use of synthetic phytohormones, and genetic engineering (Chieb & Gachomo, 2023; Mondlhane et al., 2025). Nevertheless, these techniques are time consuming and expensive (Chieb & Gachomo, 2023). Thus, economical and sustainable practices, such intercropping of grain legumes with cereal crops (Kiwia et al. 2019; Etesami et al. 2022), represent an option to mitigate the effects of drought. This practice is fundamental mostly in agricultural systems with low use of inputs and it has been shown to be a suitable way of ecological intensification since allows to maximise the use of resources, such as land, water, nutrients and consequently, it increases crops productivity (Stomph et al. 2019).

Several studies carried out in Mediterranean areas, such as those by Latati et al. (2017) and Bouras et al. (2023) in Algeria, Querné et al. (2016) in France, Ruisi et al. (2017), Di Miceli et al. (2022) and Leoni et al. (2022) in Italy, have shown that intercrops have significant yield advantage as compared with monocrops. However, other studies have not reported any effect of intercrop (Sermenli et al. 2007; Castillo et al. 2022). This is because the effectiveness of an intercropping system depends on several factors, such as crop species and genotypes, water availability and other multiple factors to be taken into account in the agronomic management.

Intercropping provides the possibility of yield benefits, mainly if the mixed crops are complementary (Fonteyne et al. 2023). For instance, in maize-legume-cucurbit intercropping, there is a complementarity once they have different heights which allows receiving light differently, furthermore, the legume fix N which can be used by other crops, while cucurbits leaves shade the ground controlling weeds and conserving soil moisture (Fonteyne et al. 2023). These crops are commonly cropped individually in central Chile; however, water scarcity, because of erratic rainfall in the region, represents a challenge for their cultivation, as they are quite sensitive to water deficit (Tapia et al. 2022), which has severely led to low crop yields (Mo et al. 2016). As many smallholder farmers depend on rainfall, a strong limitation to supplement with irrigation due the multi-year drought since 2010 (Garreaud et al. 2019, Alvarez-Garreton et al. 2021, Fernández et al. 2023, Alvarez-Garreton et al. 2024). Hence, under these circumstances, research must urgently provide robust tools, economically viable and environmentally friendly practices, which allow to enhance crop productivity.

Therefore, the current study was undertaken to analyse the compatibility between different species of legume and cucurbits growing in association with maize, as a starting point which allows to determine the best combinations to be established in intercropping systems in Central Chile. This objective was achieved by testing the following two hypotheses: (a) intercropping system changes the morphological and physiological traits of the crop species mixed; and (b) water restriction adversely affects the morphological and physiological traits of crop species.

MATERIALS AND METHODS

Experimental design and treatments

Controlled pot experiments were conducted under greenhouse conditions at Centro Ceres, Quillota, Chile. The study was conducted using a 13 X 2 bifactorial experiment in a completely randomised design with three replications per treatment (N = 78). The 13 treatments represented cropping system using monospecific, dual and triple combinations of plant species, while the 2 levels of the second factor were the irrigation levels (40% and 100% of water holding capacity (WHC) of substrate, named as R100 and R40, respectively). In the experiment, three types of crops were used, including maize as cereal and the main crop; and including two pulse crops: common beans (*Phaseolus vulgaris* L.) and chickpea (*Cicer arietinum* L.); and two cucurbits: pumpkin (*Cucurbita maxima*) and cucumber (*Cucumis sativus*). These are traditional crops used in “*milpa*”, a “Mesoamerican triad”, which consists basically of maize, common bean and squash (Fonteyne et al. 2023). The five plant species were cropped as: i) sole crop (T1, T2, T3, T4 and T5, corresponding to maize, common bean, chickpea, pumpkin and cucumber, respectively) ii) in two species intercrops (T6, T7, T8 and T9, maize and common bean, maize and chickpea, maize and pumpkin, and maize and cucumber, respectively); iii) and three species intercrops (T10, T11, T12 and T13, maize, common bean and pumpkin; maize, common bean and cucumber; maize, chickpea and pumpkin; and maize, chickpea and cucumber, respectively). In each pot only a single crop species plant has been transplanted.

Plant Growth Conditions and Experimental Design

Sowing was carried out in a tray under greenhouse average temperature and humidity near to 16º C and 72.9%, respectively. Before sowing, the seeds were immersed in 4.9% w/v sodium hypochlorite solution for 10 min, to disinfect them and then washed three times with distilled water. Trays were hand-irrigated with clear, tap water. Six weeks later, after germination, the seedlings were transplanted to 1.5 L polyethylene plastic pots. A soilless substrate comprising 30% perlite, 20% vermiculite and 50% coconut coir (v/v/v) was used after being properly sterilized at 121º C for 20 min to eliminate microorganisms that could influence the results of the experiment.

Determination of relative growth rate, biomass yield and land equivalent ratio (LER)

Forty-five days after transplantation, morphological growth traits such as plant height, root and shoot biomass were collected at the end of the experiment for all treatments. Plant height was measured using a measuring tape. In this study, we considered the distance between the ground and the plant´s highest point for each plant (Ramesh et al. 2023). With height data, relative growth rate was estimated as: $RGR = (\ln H_{t2} - \ln H_{t1})/(t_2 - t_1)$; where H_{t1} and H_{t2} are plant height at t_1, the time of first measurement when transplantation was done and t_2, the time of the second measurement, at the end of the experiment, respectively (Simonetti et al. 2007).
For fresh shoot and root biomass determination, plants were harvested and weighed for each plant before storing at -80º C for further analyses. Notwithstanding, for intercrops was difficult to separate roots per crop, therefore we weighed total belowground biomass. Finally, the land equivalent ratio (LER) was calculated as the sum of the fractions of the aboveground biomass of intercropped crops relative to their sole crop biomass at the same watering level (Glaze-Corcoran et al. 2020). The LER was computed by the following formula:

$$LER = \sum \frac{Biomass\ i}{Biomass\ m}$$

Where:
Biomass *i*: the biomass of each individual crop in the intercropping
Biomass *m*: the biomass of the same crop in a monocrop

Photosynthetic efficiency

To determine how water restriction influenced photosynthesis parameters, at the end of the experiment, chlorophyll fluorescence variable of quantum yield (Qy) was measured using the FluorPen FP100 (Photon Systems Instruments, Drasov, Czech Republic), non-invasive assessment, in the second youngest leaf of each plant after 15 to 20 minutes of leaf adaptation to darkness. This quantifies the photochemical quantum yield of photosystem II (PSII) as the ratio between the actual fluorescence yield in the light-adapted state (F_v) and the maximum fluorescence yield in the light-adapted state (Fm), according to Oxborough and Baker (1997).

Photosynthetic pigments quantification

The photosynthetic pigments chlorophyll *a* (Chl *a*), chlorophyll *b* (Chl *b*), total chlorophyll (Chl total) and carotenoid (Car) contents were quantified from leaf extracts obtained using 80% acetone following the established protocols of Lichtenthaler (1987). Briefly, 0.2 g of ground leaf of plant was mixed with 15 mL 80% acetone and shaken. Subsequently, the samples were centrifugated for 10 min

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at 5000 rpm and then the supernatants were collected and filtered through paper filter Whatman N°1 and transferred to a 15 mL tube. Following, the absorbance at wavelengths 663.2, 646.8 and 470 nm was measured using UV-vis spectrophotometer (Genesis 10S; Thermo Scientific®, Waltham, Mass., U.S.A.) to assess Chl *a*, chl *b*, and Car, respectively.

Leaf water potential

To determine how deficit irrigation affected crop water status, leaf water potential was measured on each plant for all treatments on mature leaves of the upper third of the plant fully expanded leaflets during the central hours of illumination (from 12:00 to 15:00 h) (Cotrozzi et al. 2017). The leaves were covered with a plastic bag with aluminium foil during 20 minutes, excised from the main stem with a sharp blade, and quickly placed in the Scholander-Hammel moisture pressure chamber, leaving enough petiole to be inserted into the nozzle of the pressure chamber. Compressed nitrogen gas was used to increase the pressure in the chamber following Bañón et al. (2022) methodology.

Data analysis

Two-way ANOVA was performed after the verification of the statistical assumptions of normality and homoscedasticity of data, using Shapiro-Wilks and Levene Tests, respectively. Additionally, the values for each treatment were expressed as the mean ± standard error of the mean (SE). Tukey´s method was used to compare the means for each variable ($P < 0.05$). All calculations and statistical analyses were performed using R software version 4.3.1.

RESULTS AND DISCUSSION

Fresh biomass production

Biomass was dependent on the irrigation level, cropping system ($p < 0.001$), and the interaction of both factors ($p < 0.01$) (Fig. 1). The maize associated to common bean and pumpkin (T10) under full watering (R100) reached the highest root biomass and it was significantly different to all the other treatments (Fig. 1a). The associated crops in T10 are highly complementary, which allow greater volume of crop roots (Fonteyne et al. 2023). However, under water restriction, T8 and T10 registered no statistical differences (Fig. 1b). Thus, our observations of root biomass showed that water regime affected more than the crop species associated. There is contradictory evidence on the effect of water-limited conditions on root growth. For instance, Poomkokrak et al. (2024), reported a stimulation of root growth due water starvation in cherry tomato. Nonetheless, Filho et al. (2024) suggest that under a severe water limitation (50% of WHC), a significant decrease of plant root biomass production was observed. This is consistent with our results, as we imposed water limitation at 40% of WHC. Even though lower root biomass production, our results showed that some intercropping systems (T8- maize and pumpkin) stimulate the production of root biomass.

In turn, for shoot biomass, there were no differences between T12 (maize associated to chickpea and pumpkin) and T8 (maize and pumpkin) under R100, but they were both significantly different compared to all other treatments (Fig. 1c). Nevertheless, water shortage reduced the shoot biomass in both previous treatments (Fig. 1d). This aligns with the findings of Aslam et al. (2013), who reported that under water-limited conditions, maize experiences reduced photosynthesis, transpiration, and light interception, ultimately affecting crop traits due to a decrease in translocated assimilates. El-Beltagi et al. (2022) also reported a similar finding for chickpea, where drought stress during the vegetative phase reduced shoot biomass. Even though pumpkins are considered drought-tolerant (Liu et al. 2023), Seymen et al. (2019) reported significant plant length reduction due drought stress, once under these conditions meristematic cell divisions and subsequent massive expansion of young cells are inhibited. Furthermore, in this situation, photosynthesis is reduced, which consequently impacts the biomass production.

For total fresh biomass, the T8 and T10 crops under R100 watering condition did not differ between them, but they were both statistically higher than all the other treatments (Fig. 1e). For both treatments, a significant decrease ($p \leq 0.001$) on total fresh biomass was recorded under restricted irrigation (Fig. 1f). Nevertheless, the same treatments presented the highest values when compared to other treatments in the same conditions of restricted watering, suggesting a good compatibility among associated crops.

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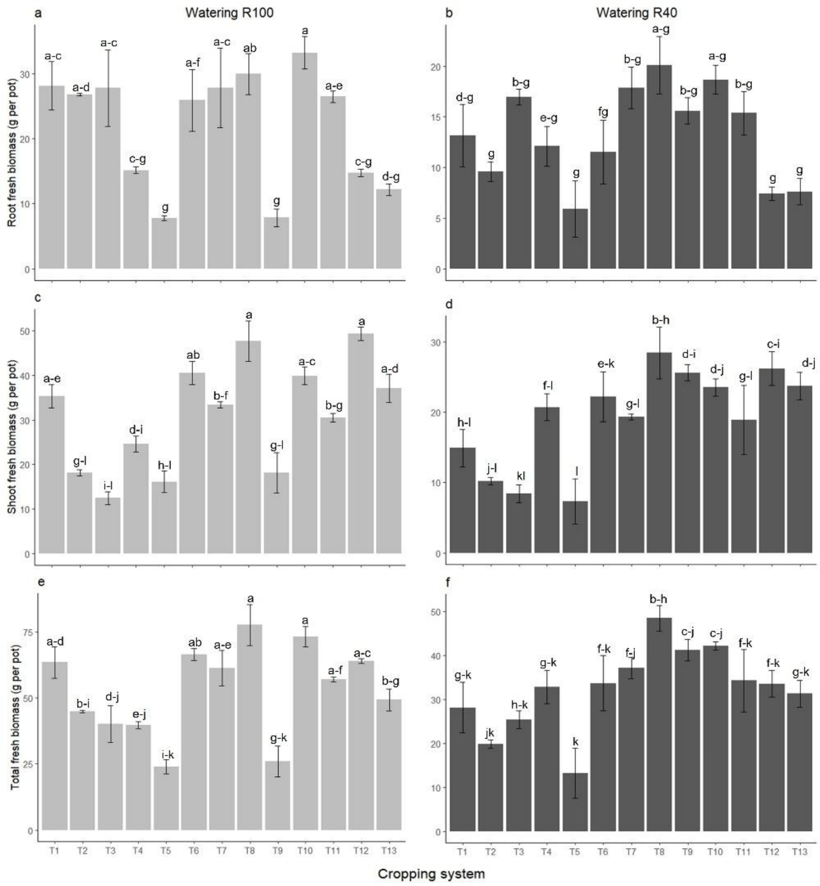

Fig. 1. Differences in root, shoot and total fresh weight biomasses (g pot^{-1}) grown under different irrigation level and cropping system. Different letters following the mean values (±S.E.) indicate statistical differences among treatments (p < 0.05). Legend**:** T1, T2, T3, T4 and T5, correspond to maize, common bean, chickpea, pumpkin and cucumber, respectively in monocrop; T6, T7, T8 and T9, maize and common bean, maize and chickpea, maize and pumpkin, and maize and cucumber, respectively; T10, T11, T12 and T13, maize, common bean and pumpkin; maize, common bean and cucumber; maize, chickpea and pumpkin; and maize, chickpea and cucumber, respectively.

Land Equivalent Ratio

The competition index depended only on irrigation level ($p < 0.05$). The LER values for all intercropping treatments were on average greater than 1.0 regardless irrigation level, except T9 under R100 (Fig. 2a and b). Thus, this observation suggests an advantage in the intercropping over their monocrops, once more land should be required under sole cropping to produce the same biomass quantity

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achieved under intercropping (Ramesh et al. 2023). In this study, our median LER was 1.30, which is greater than the median LER of 1.17 reported by Yu et al. (2015) in a global-scale meta-analysis of hundred studies. Even though, the LER values for biomass yield can be used to quantify the intercrop productivity of an intercropping system, but they cannot be used to interpret competitive interactions (Martin-Guay et al. 2017; Galanopoulou et al. 2019).

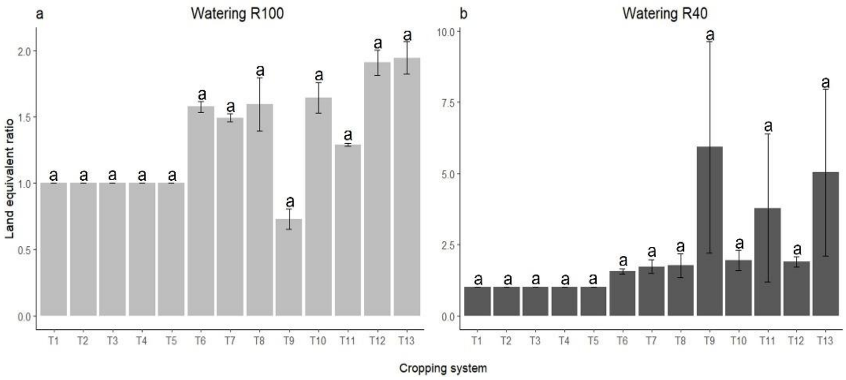

Fig. 2. Land equivalent ratio (LER) for monocrops and intercrops grown under different irrigation level on for fresh shoot biomass weight. Different letters following the mean values (±S.E.) indicate statistical differences among treatments ($p < 0.05$). Legend**:** T1, T2, T3, T4 and T5, correspond to maize, common bean, chickpea, pumpkin and cucumber, respectively in monocrop; T6, T7, T8 and T9, maize and common bean, maize and chickpea, maize and pumpkin, and maize and cucumber, respectively; T10, T11, T12 and T13, maize, common bean and pumpkin; maize, common bean and cucumber; maize, chickpea and pumpkin; and maize, chickpea and cucumber, respectively.

Height

There were found significant differences for both factors and its interaction ($p < 0.001$). The maize in intercrop with pumpkin (T8) under R100 was significantly higher among other crops (Fig. 3a). In general, water deficit caused reduction of plant height (Fig. 3b). The decrease in height could be attributed to drop in cell enlargement and more leaf senescence under water limitations (Manivannan yet al. 2007). Analysing crop by crop, we observed that maize plant height was substantially greater in intercropping than in sole crop height (3 to 4.6-fold lower) when subjected to water restriction conditions. Notwithstanding, Anyoni and co-workers (2023), did not notice difference on maize height due intercropping effect. Legumes did not differ on plant height due cropping system in R100 conditions, whereas under R40, intercropping generally presented lesser height. This is in accordance with what stated by Li et al. (2020), that under intercropping the plant height could be smaller than in sole cropping likely due to reduced competition for resources such as light with companion crops. Cucurbits were higher in sole

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cropping, while when subjected to water-limitation, cucumber increased its height under intercrops.

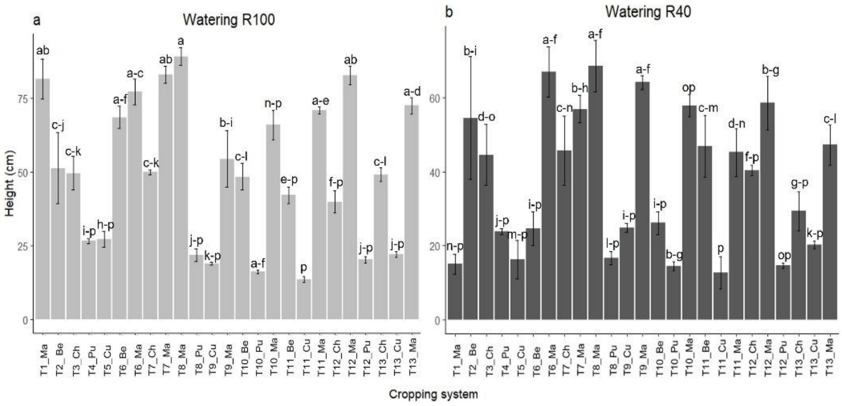

Fig. 3. Plant height (cm). Different letters following the mean values (±S.E.) indicate statistical differences. Legend**:** T1, T2, T3, T4 and T5, correspond to maize, common bean, chickpea, pumpkin and cucumber, respectively in monocrop; T6, T7, T8 and T9, maize and common bean, maize and chickpea, maize and pumpkin, and maize and cucumber, respectively; T10, T11, T12 and T13, maize, common bean and pumpkin; maize, common bean and cucumber; maize, chickpea and pumpkin; and maize, chickpea and cucumber, respectively; Ma (maize); Be (common bean); Ch (chickpea); Pu (pumpkin) and Cu (cucumber).

Relative growth rate

The plant relative growth rate was significantly different for irrigation level ($p < 0.05$), cropping system and its interaction ($p < 0.001$). Overall, maize at T9 (maize and cucumber) presented higher RGR than all other crops, regardless of irrigation level (Fig. 4a and b). This result suggests that maize associated to cucumber behaves like a dominant crop, once seems to be more successful in extracting water for its benefit. For instance, Chowdhury and Rosario (1992) in maze and mung bean intercropping reported a reduction of associated mung bean due to N application of more than 30 kg ha^{-1}, whereas maize increased dry-matter and grain yield. In general, water restriction has decreased the RGR. On the other hand under water-limitation conditions, the intercropping presented greater RGR over sole crop; in common bean under R100, no differences were observed, except for T6 (maize and common bean), whereas under R40, sole cropping increased its RGR; in chickpea T7 (maize and chickpea) presented higher RGR, even though there were no differences with sole crop under R100; pumpkin exhibited higher RGR in sole crop compared to intercropping, regardless the irrigation level; and the cucumber had higher RGR value in T9 (maize and cucumber) either R100 or R40.

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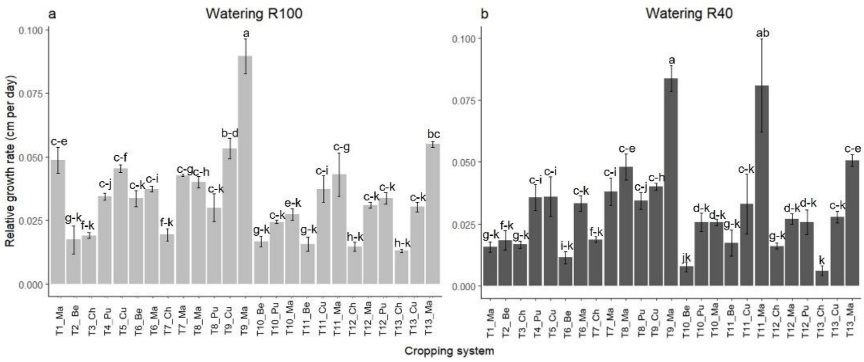

Fig. 4. Relative crop growth rate (cm day^{-1}). Different letters following the mean values (±S.E.) indicate statistical differences. Legend**:** T1, T2, T3, T4 and T5, correspond to maize, common bean, chickpea, pumpkin and cucumber, respectively in monocrop; T6, T7, T8 and T9, maize and common bean, maize and chickpea, maize and pumpkin, and maize and cucumber, respectively; T10, T11, T12 and T13, maize, common bean and pumpkin; maize, common bean and cucumber; maize, chickpea and pumpkin; and maize, chickpea and cucumber, respectively; Ma (maize); Be (common bean); Ch (chickpea); Pu (pumpkin) and Cu (cucumber).

Quantum yield and photosynthetic pigments

Quantum yield presented differences due to cropping system ($p < 0.001$) and the interaction between cropping system and irrigation level ($p < 0.01$). The bean in monocropping (T2) had a higher Qy than all other treatments, regardless of irrigation level (Fig. 5a and b). The results suggest that bean in monocrop possesses a higher photochemical efficiency, which means that the absorbed light is efficiently used by PSII (Nemali & van Irsel, 2008). Within each crop, maize (T6; maize and bean) under R100 presented higher Qy whereas under R40, sole maize exhibited the higher Qy. For bean and the cucurbits under sole cropping performed higher Qy regardless of the watering conditions. This may be due the absence of shade from other crops, as the shade has a negative impact on short architecture crops photosynthesis, once maize is able to utilise light energy more efficiently (Qiang et al. 2024). Finally, for chickpea, the higher values were obtained in T7 (maize and chickpea) and T12 (maize, chickpea and pumpkin) under R100 condition, while at R40 conditions, monocrop registered the lesser Qy.

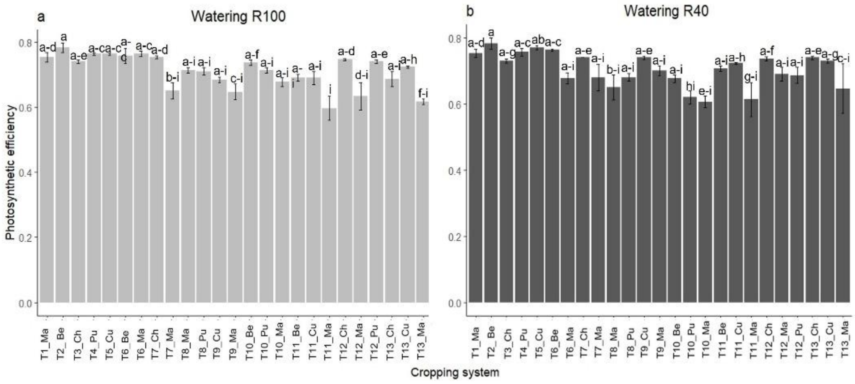

Fig. 5. Quantum yield efficiency. Different letters following the mean values (±S.E.) indicate statistical differences. Legend**:** T1, T2, T3, T4 and T5, correspond to maize, common bean, chickpea, pumpkin and cucumber, respectively in monocrop; T6, T7, T8 and T9, maize and common bean, maize and chickpea, maize and pumpkin, and maize and cucumber, respectively; T10, T11, T12 and T13, maize, common bean and pumpkin; maize, common bean and cucumber; maize, chickpea and pumpkin; and maize, chickpea and cucumber, respectively; Ma (maize); Be (common bean); Ch (chickpea); Pu (pumpkin) and Cu (cucumber).

All the pigments showed statistic differences depending only on the cropping system. Chl *a* content did not differ among treatments in both water conditions (Fig. 6a and b). For Chl *b* content, cucumber intercropped with maize (T9) under R100 presented the highest value (719.56 µg g^{-1} based on fresh weight; Fig. 6c). However, water restriction decreased the content of Chl *b* by 2.30% in the same crop (Fig. 6d). With respect to the cropping system, an increase of chl *b* in chickpea and cucumber when intercropped was observed. Chl total content was higher for cucumber intercropped with maize (T9), regardless the irrigation level (Fig. 6e and f). Regarding to Chl total, monocrop of bean showed a noticeable decrease in comparison with the other treatments. Finally, for Car, the highest content value was registered in chickpea intercropped with maize under R40 (Fig. 6h), which represented an increase of about 44.48% when compared with R100 (Fig. 6g).

Water deficit conditions in plants adversely affect many physiological and biochemical processes, such as photosynthesis, cell growth, chlorophyll synthesis and carbon metabolism (Sharma et al. 2025). Hence, we expected a reduction of chlorophyll concentrations due to the degradation and photo-oxidation of chlorophyll under these conditions. Nonetheless, in the current study, regarding water restriction, no significant differences were found in photosynthetic pigments, which aligns with findings reported by Santander et al. (2024) and Pérez-Moncada et al. (2024), which suggest that these crops presented higher photo-inhibition of PSII under water scarcity.

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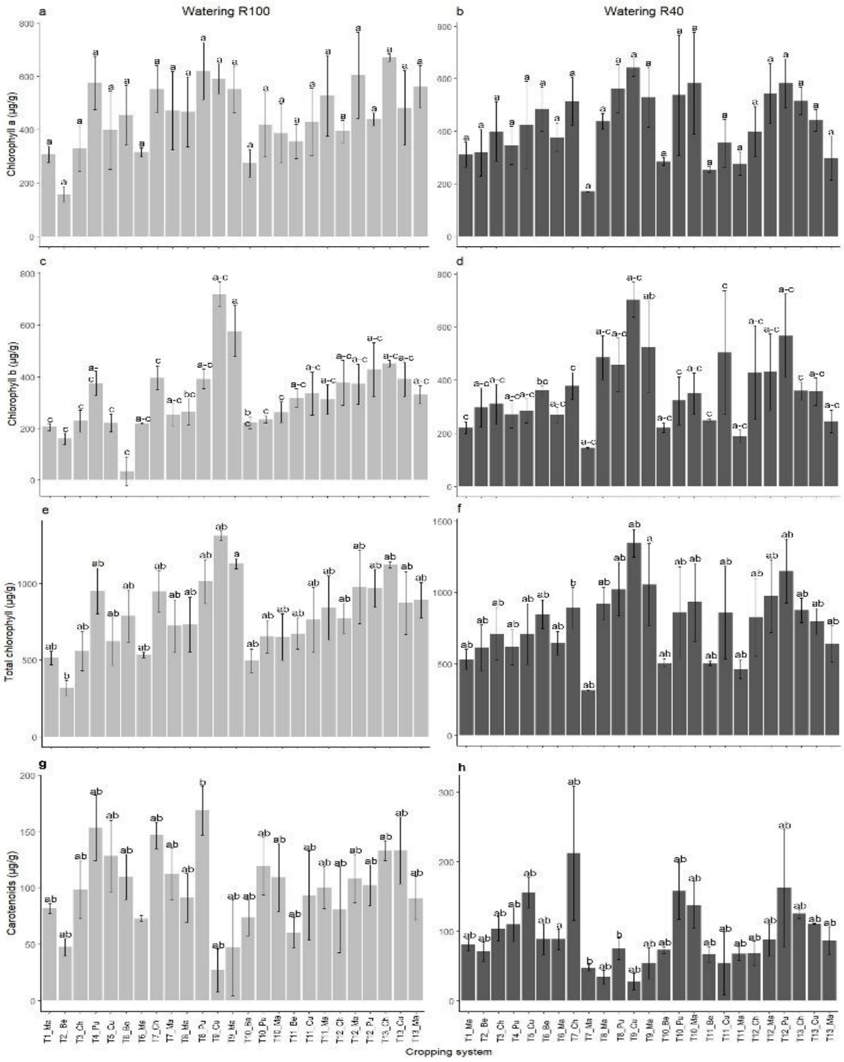

Fig. 6. Effects of water restriction and cropping system on (a and b) chlorophyll a, (c and d) chlorophyll b, (e and f) total chlorophyll and (g and h) carotenoids under R100 and R40. Different letters following the mean values (±S.E.) indicate statistical differences. Legend**:** T1, T2, T3, T4 and T5, correspond to maize, common bean, chickpea, pumpkin and cucumber, respectively in monocrop; T6, T7, T8 and T9, maize and common bean, maize and chickpea, maize and pumpkin, and maize and cucumber, respectively; T10, T11, T12 and T13, maize, common bean and pumpkin; maize, common bean and cucumber; maize, chickpea and pumpkin; and maize, chickpea and cucumber, respectively; Ma (maize); Be (common bean); Ch (chickpea); Pu (pumpkin) and Cu (cucumber).

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Leaf water status

The leaf water potential only depended on cropping system ($p < 0.001$). In the maize at T1 and T7 under R40 presented higher significant leaf potential values, but not different between them (Fig. 7b) and the lowest in T12 under no water restriction (Fig. 7a), whereas other treatments did not differ among them. These results suggest a good performance of maize, which showed more drought tolerance, as this trait has been related to plant tolerance to water deficit since it reflects its ability to absorb the water available in the soil under water starvation conditions, thus avoid tissue dehydration, which is probably due deeper root growth over companion crops, as observed in other cereals like wheat in the studies of Bedoussac & Justes (2010) and Hadir et al. 2025. This improvement in water status for maize has a beneficial effect on the accumulation biomass ability, as it is strongly associated to stomatal opening and CO_2 absorption for carbohydrate synthesis (Filho et al. 2024). Therefore, this situation protects the crop from drastic effects of drought, once the decline in water leaf potential can drive to reduction in plant height, as reductions in water potential inhibits leaf expansion (Bergonic et al. 2000). Bean in (T6 and T10, under R40) and T11 under R100 had the higher values with this crop and did not differ among them and T2 under R40 was the lowest value registered. Chickpea, pumpkin and cucumber did not differ within each crop.

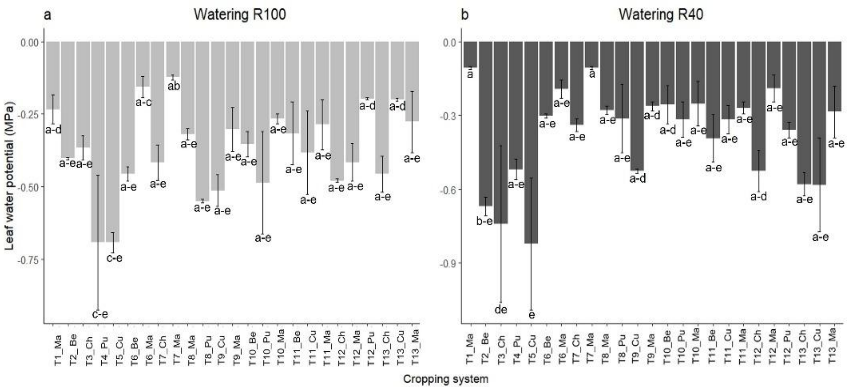

Fig. 7. Leaf water potential (MPa). Different letters following the mean values (±S.E.) indicate statistical differences. Legend**:** T1, T2, T3, T4 and T5, correspond to maize, common bean, chickpea, pumpkin and cucumber, respectively in monocrop; T6, T7, T8 and T9, maize and common bean, maize and chickpea, maize and pumpkin, and maize and cucumber, respectively; T10, T11, T12 and T13, maize, common bean and pumpkin; maize, common bean and cucumber; maize, chickpea and pumpkin; and maize, chickpea and cucumber, respectively; Ma (maize); Be (common bean); Ch (chickpea); Pu (pumpkin) and Cu (cucumber).

CONCLUSIONS

The morphological traits of all crops were markedly influenced by both water deprivation and the cropping system, whereas physiological characteristics and photosynthetic pigments were mainly impacted by the latter. Root and shoot biomass, height and relative growth rate decreased due water deficit, confirming the strong impact of drought on vegetative development. The land equivalent ratio varied according to irrigation level; however, intercropping consistently outperformed monocropping, even under water restriction, demonstrating its ability to improve resource use efficiency and productivity stability.

Photochemical efficiency tended to increase under monocropping, while intercropping maintained higher leaf water potential, suggesting improved water status in the mixture systems. In maize, the higher chlorophyll *b* and carotenoid contents observed in some intercropping combinations indicate possible adjustments to light utilization and photoprotection.

Overall, our findings confirm that water shortage negatively affects negatively morphological and physiological performance of crops but also highlight the potential of maize-common bean-pumpkin intercropping as an effective strategy to mitigate drought stress. These results support the view that diversified cropping system can contribute to greater resilience and sustainability in agricultural production under water-limited conditions.

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Conflict of interest

The authors declare no relevant financial or non-financial interests that are directly or indirectly related to the manuscript submitted for publication.

Author contribution

Conceptualization: C.M. and P.C. Methodology: C.M., O.T-L., C.G., T.S., R. C., C. S., P.C. Resources: P.P., C.H., P.C. Writing the original draft: C.M. and P.C. Writing-review and editing: all the authors. Funding acquisition: P.P., C.H. and P.C. All the coauthors reviewed the final version and approved the manuscript before submission.

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