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Biological responses of barley as affected by soil moisture and cationic balance in Brazil

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Abstract. Control of water in the soil-plant-atmosphere system is vital to assure maximization of crop yield. Nutrients uptake by the plants is considerably affected by soil moisture mainly because mineral nutrients reach out for roots as a function of mass flux and diffusion. Soil cationic balance might impinge upon calcium (Ca), magnesium (Mg) and potassium (K) uptake by the plant roots. In light of the hypothesis that soil Ca:Mg ratio more suitable for agricultural crops hinges upon soil moisture, the current research aimed to study interrelationships between soil moisture status and cationic balance in soil on biological responsiveness of barley plants. The experiment was conducted in a protected environment and a randomized complete block design was used with three replicates arranged in a 4×4 factorial scheme. Soil water treatments imposed herein were defined as a function of four fractions of maximum crop evapotranspiration (ETm): 60, 80, 100, and 120% ETm along with four ratios between calcium (Ca) and magnesium (Mg): 1:1, 3:1, 6:1, and 9:1. The parameters evaluated were: plant height, number of tillers, number of ears per plant, number of grains per ear, number of grains per plant, grain weight per plant, and thousand-grain weight. Soil cationic balance did not impinge upon agronomic performance of barley crop, whereas all of response-variables evaluated were highly governed by soil water availability. Conversely, the most adequate soil Ca:Mg ratio to promote the best biological responsiveness of barley grown under a protected environment did not depend on soil moisture levels.

Key words: *Hordeum vulgare* L., soil humidity, soil Ca:Mg ratio, grain yield, soil fertility.

INTRODUCTION

Water is fundamental for the biochemical and physiological processes, playing a role as a universal solvent in order to promote transport of minerals, gases and solutes in the soil-plant-atmosphere system along with plant thermal regulation by means of crop transpiration (Costa, 2001). Water flux in the system of soil-plant-atmosphere takes place under a direct or indirect influence of atmosphere evaporative demand or reference evapotranspiration (ETo).

Uptake of mineral nutrients by the crops is highly affected by soil moisture status, once most of the macronutrients reach the roots of the plants mainly by means of mass flux and diffusion (Domingues et al., 2026). According to Barber (1974), the number of ions transported by mass flux is determined by the ion's concentration in soil solution in conjunction with crop maximum evapotranspiration (ETm or ETc).

Ca and Mg macronutrients are transported by mass flux process (Barber, 1974). Since such mineral nutrients are transported to plant roots by water, lack of water leads to reductions in mass flux of soluble nutrients in water, such as Ca and Mg (Clair & Lynch, 2010). Therefore, water deficit situations negatively affect mineral nutrition and crop growth (Marques et al., 2023).

Cationic balance prevailing in soil solution might compromise uptake of a given nutrient by the plant roots. Calcium (Ca), magnesium (Mg) and potassium (K) compete for the same sites of adsorption and absorption, as well as transportation to radicular surfaces. Excess of one particular nutrient inhibits absorption of another, culminating in nutritional deficiency symptoms in plants.

Soil cationic balance might affect agronomic performance and physiological responses of the studied agricultural crops. Under high concentration of a given specific-cation in soil solution, inhibition in absorption of other cation might be conducive to nutritional deficiency symptoms and compromise substantially biological responses of the plants. However, the impact of soil cationic balance on commercial yields turns out to be strongly driven by specie, cultivar, soil type, and prevailing microclimatic conditions of the cropping system (Domingues et al., 2026).

With the purpose of providing adequate levels of Ca and Mg in soil, several scientists recommend application of calcium sulphate and calcareous with high content in Ca (Soto et al., 2023). Nevertheless, insofar as soil Ca:Mg ratios increase Mg and K uptake is impaired by the excess of Ca absorbed by the plants (Medeiros et al., 2008). K turns out to be the macronutrient that most favours grains filling, since high levels of Ca and Mg in soil solution substantially compromise K uptake and, therefore, reduce crop yields (Lange et al., 2021). Soto et al. (2023) highlights that Ca improves soil aggregation and plays an important role in stabilization of carbon, whereas Mg reduces soil aggregation and water infiltration processes. Another main contribution factor concerning soil cationic balance as a cultural practice to be borne in mind is that it betters both nutrients availability and also biological responses of plants in such a manner as to maximize crop commercial yields and minimize costs of production in cropping systems (Chaganti et al., 2021).

Root cation exchange capacity (root CEC) is lower in monocots than in dicots, allowing them to absorb more nutrients (Asher & Ozanne, 1961). For cereals, such as maize, wheat, and rice root CEC varies from 100 to 200 mmolc kg^{-1} of dry roots, whereas for legume crops, such as soybean and common bean root CEC ranges from 400 to 800 mmolc kg^{-1} of dry roots (Fernandes & Souza, 2006). Williams & Coleman (1950) verified that root CEC of soybean was twice as much of that found for maize. Once root CEC interferes with uptake of cations and transport of Ca and Mg from soil solution to rhizosphere is regulated by mass flux mechanism, it is rather expected that soil Ca:Mg ratio more suitable for crop growth depends on crop metabolism in conjunction with root CEC and soil moisture levels (Schneider et al., 2017; Domingues et al., 2026).

Barley (*Hordeum vulgare* L.) is considered one of the most antique agricultural species in the world and is well-adapted to several environments and different latitudes (Dawson et al., 2015; Newton et al., 2011; Dellabiglia et al., 2025). Due to some special properties, barley crop might adapt to different unfavourable climatic conditions as opposed to other agricultural crops (Zargar et al., 2018). Apart from being utilized either for human or animal nutrition, barley is employed as a raw matter for beer brewing industries owing to its malt characteristics (Hong & Zhang, 2020). With a world production in 2023 of roughly 145 million tons, barley turns out to be the fourth cereal mostly grown in the world, remaining behind only rice, wheat, and maize (FAOSTAT, 2025). Under a national perspective, an estimation of commercial yields of the aforementioned winter cereal throughout the 2024 harvest was corresponding to slightly over 511-thousand tons (CONAB, 2025).

Barley crop is a target of several interference factors that preclude remarkable yields to be achieved in commercial production fields (Mulatu & Lakew, 2011). Among such factors, it is well known that soil acidity, low availability of nutrients in soil solution, insufficient drainage within soil profile, soil moisture deficits and inadequate agricultural practices are those which considerably promote abiotic stresses associated with yield gaps (Agegnehu et al., 2016; Jahromi et al., 2023). In view of such a problem, we hypothesized that soil cationic balance interferes with barley crop biological responses only under soil water deficiency conditions. In order to test this scientific hypothesis formulated by Soto et al. (2023), we stablished four different soil Ca:Mg ratios along with four distinct soil moisture levels to assess the impacts of such factors on barley agronomic performance. Thus, the current work aimed to scrutinize and comprehend existing relationships between soil humidity regimes and soil cationic balance on biological responsiveness of barley grown in a protected environment under edaphoclimatic conditions of Ponta Grossa, State of Paraná, Brazil.

MATERIAL AND METHODS

Site description and agricultural environment

The experiment was carried out in a greenhouse belonging to the State University of Ponta Grossa, Parana State, Brazil (25°5'40''S, 50°9'48''W and 956 m above sea level). The climate at the site cultivated with barley, according to the Köppen and Geiger classification, is categorized as a Cfb type (mesothermal, humid, subtropical), with mean air temperature of the coldest month below 18 °C, with fresh summers, mean air temperature of the hottest month below 22 °C and bereft of a well-defined dry season. The mean annual precipitation ranges from 1,400 to 1,600 mm, with August considered the driest month and February the rainiest one (Nitsche et al., 2019). Soil type collected from 0–20 cm-layer was a Cambisol, with soil samples seized, homogenized, and dried at atmospheric air prior to its incubation.

Experimental design, treatments, and experiment conduction

In light of cultivation of a promising genotype of barley at a commercial scale selected at Southern of Brazil, an experiment was installed and conducted under a protected environment considering a randomized complete block design with three replicates arranged in a 4×4 factorial scheme. Treatments were constituted of four levels of soil water (60, 80, 100, and 120% of maximum crop evapotranspiration – ETm) and four soil Ca:Mg ratios (1:1, 3:1, 6:1, and 9:1), which were applied to 18 kg of dry soil allotted in flexible plastic vases.

Soil water treatments were defined from the knowledge on crop water consumptive use (ETm). Therefore, distinct fractions of ETm were adopted with the aim of assessing the impact of both soil water status and soil cationic balance on response-variables, which were expressed by barley agronomic parameters.

Water treatments were adopted at the moment from which barley plants showed the second leaf entirely developed. Irrigation was applied based on gravimetric daily measurements of soil water content by means of a precision scale. Before imposition of water treatments, all vases received the same amount of irrigation water in order to assure that initial soil water supply was near or at pot capacity condition. For definition of soil Ca:Mg ratios, results of soil chemical analysis on soil samples placed in all vases were taken into consideration along with the need for addition of $CaCO_3$ and $MgCO_3$ to soil as a function of Ca:Mg ratios previously stablished.

In order to assess the effect of different Ca:Mg ratios on biological responses of barley, soil samples were subjected to incubation process before sowing. Therefore, dry soil was mixed with $CaCO_3$ (p.a.) and $MgCO_3$ (p.a.) analytical reagents to make sure that all soil cationic balance treatments stipulated in the experiment were reached.

Shortly after soil collection, drying, seizing and homogenization practices, a soil sample was collected to proceed granulometric and chemical analyses (Table 1). The purpose of the chemical analysis was to determine $CaCO_3$ and $MgCO_3$ amounts to be mixed in the soil aiming at achieving Ca:Mg ratios imposed as treatments, as well as to define precise fertilizer doses to be applied to the soil placed in the vases.

Table 1. Soil chemical and granulometric attributes before barley experiment installation under protected environment at Ponta Grossa, PR, Brazil, 2024

pH ($CaCl_2$)	H+Al	Al^{3+}	Ca^{2+}	Mg^{2+}	K^+	CTC $_{(pH\ 7.0)}$
	------------------------------------ cmol$_c$ dm^{-3}------------------------------------					
4.5	5.61	0.5	1.4	0.4	0.06	7.47
P (Mehlich^{-1})	C-organic	Sand	Silt	Clay	Base saturation	
mg dm^{-3}	g dm^{-3}	-------------- g kg^{-1}----------------			%	
41.7	14	804	61	135	25	

CTC $_{(pH\ 7.0)}$ = potential cation exchange capacity; C-organic = Walkley-Black.

The $CaCO_3$ (p.a.) and $MgCO_3$ (p.a.) analytical reagents were utilized at the following proportions: a) 1:1 ratio – 13.50 g of $CaCO_3$ and 11.34 g of $MgCO_3$; b) 3:1 ratio – 20.30 g of $CaCO_3$ and 5.67 g of $MgCO_3$; c) 6:1 ratio – 23.22 g of $CaCO_3$ and 3.24 g of $MgCO_3$; d) 9:1 ratio – 24.34 g of $CaCO_3$ and 2.26 g of $MgCO_3$ for 18 kg of dry soil in each vase. Such products were incorporated into the soil and placed in the vases afterwards. All vases were irrigated for 60 days in order to maintain 80% field capacity throughout the entire incubation period to assure suitable soil water conditions for chemical reactions of correctives to take place in compliance with imposition of the water treatments.

Irrigation with deionized water was performed manually with the purpose of measuring different soil water supply levels. Variation in weight of the control-volume (soil plus plants grown in the vases) is directly proportional to the amount of water lost to the atmosphere of the protected environment under which barley was tilled. Thus, a precision scale was installed inside the experimental environment to determine the water ideal climatic demand of barley crop (ETm).

In order to guarantee a suitable water supply in the soil compatible to occurrence of maximum crop evapotranspiration (ETm), soil water content is supposed to be at or near field capacity. Under controlled environmental conditions, such a field capacity comes to being denominated as pot field (Casaroli & Lier, 2008), which is given by cessation of descending movement of gravitational water within soil profile placed in the vases.

With the purpose of determining ETm we made use of gravimetry methodology. Apart from the utilized flexible plastic vases for the experiment conduction, four more pots cultivated with barley plants were taken into consideration to measure ETm. Such recipients were irrigated up until vase capacity was reached, weighed and weighed again after a three day-period. The difference of mass for the soil-plant set between the moment vase capacity was reached and the final three day-period corresponds to the ideal water amount to be applied to each one of the vases – ETm. All of the vases were irrigated in compliance of soil moisture treatments. Such treatments were stablished as a function of four different fractions of ETm, such as 60%, 80%, 100%, and 120% ETm.

Sowing of barley was made in 48 12-L vases filled with seized dry soil on May 12th, 2023, shortly after soil incubation. Each experimental unity was depicted by one-single vase containing six plants belonging to Imperatriz cultivar. This particular genotype of barley was chosen owing to its late-growing cycle crop well-adapted to southern regions of Brazil, depicting an excellent resistance to foliar diseases in order to reduce costs with fungicide applications along with the highest productive potential that culminated in yields excelling previous commercial cultivars recommended for the region in study.

Sowing was manual with twelve seeds per vase placed beside central fertilization furrow. After emission of the first leaf, thinning was made with the purpose of maintaining six plants per vase. Fertilization was realized with 3.02 g of 3–17–00 ($N–P_2O_5–K_2O$) formulation plus 0.37 g of urea in central furrow of the soil shortly before sowing along with 0.86 g of KCl applied to soil surface followed by irrigation. Nitrogen fertilization in bands was made 15 DAE with 1.52 g of urea for each vase.

Before sowing, barley seeds were treated with Pyraclostrobin and Thiophanate-methyl fungicides and Fipronil insecticide. Throughout crop growing season, phytosanitary treatment was performed with aqueous solution fungicide Fenpropimorph in order to control net blotch (*Pyrenophora teres* Drechsler) and powdery mildew (*Blumeria graminis* f. Hordei (DC.) Speer). Visual diagnosis was carried out for identification of diseases according to Luz (1982). Control of weed infestation was manually made whenever necessary. Harvest was proceeded on October 27th, 2023, shortly after barley plants reached physiological maturation. Barley plants were cut close to the ground for assessment of crop yield components.

Biometric variables and yield components

The following barley biological parameters were evaluated herein: plant height, number of tillers, number of spikes, number of grains per spike, number of grains per plant, mass of grains per plant, thousand-grain mass.

Plant height (PH) was determined by measuring vertical distance between soil surface and insertion point of the highest spike with a ruler. Number of tillers (NT), number of spikes per plant (NSP), and number of grains per plant (NGP) were assessed by manual counting. Number of grains per spike (NGS) was calculated by ratio between number of grains produced by a given plant and number of spikes of the same plant under scrutiny.

To determine mass of grains per plant (MGP) a precision scale of the Marte make, AS 2000C model with a deviation of 0.01 g along with an error of 0.1 g was utilized. Furthermore, grain moisture was obtained by oven-drying method at 105 ± 3 °C for a 24-hour period (Brasil, 2009). From such a moisture obtained, mass of grains was adjusted to 13% of weight moisture (Eq. 1).

$$\mathrm{MGP} = \frac{100 - \mathrm{PG}}{100 - 13} \cdot \mathrm{mg} \tag{1}$$

where MGP = mass of grains per plant adjusted to 13% weight moisture (%); PG = percentage of measured grain moisture (%); mg = mass of grains (g).

The thousand-grain mass (TGM) was gauged by means of Eq. 2 after correction factor applied to grain moisture.

$$\mathrm{TGM} = \frac{\mathrm{MGP} \cdot 1{,}000}{\mathrm{NG}} \tag{2}$$

where NG = number of grains.

Statistical analysis

Experimental data related to barley agronomic performance and soil chemical properties were subjected to analysis of variance (ANOVA) with application of *F* test, considering a randomized complete block design with three replicates arranged in a 4×4 factorial scheme. Shortly before ANOVA with the aim of verifying normality of variances, Shapiro-Wilk test was applied to experimental data in order to confirm no need for data transformation technique.

In cases from which *F* test was significant ($P < 0.05$), experimental data were subjected to regression analysis approach to quantify the effects of four soil Ca:Mg ratios and four soil moisture levels on response-variables of barley plants grown under a protected environment in the municipality of Ponta Grossa, State of Paraná, Brazil. In light of interaction effects between soil moisture and cationic balance factors, the effects of treatments were unfolded. For the regression analyses, the choice on fitted-model was based on magnitude of coefficients of determination of the significant regressions at ($P < 0.05$). Statistical analyses were made by means of the R software (R Core Team, 2022).

RESULTS AND DISCUSSION

Prevailing climatic conditions and water applied

Measurements of daily maximum, minimal and mean air temperature regime, as well as reference evapotranspiration (ETo) were monitored under a protected environment throughout the whole barley crop growing season (Fig. 1). The mean air temperature comprised between flowering and grain filling stages was corresponding to 19.3 °C. Nevertheless, the maximum temperature measured at most of the critical phenological stages in study remained below 30 °C, which represents a thermal threshold compatible to requirements of C_3 plants (Kerbauy, 2004). The overall ETo value throughout the full-period of trial conduction was of 164.6 mm.

All vases were irrigated shortly after sowing with the purpose of maintaining soil water content compatible to pot capacity, which required an irrigation water amount corresponding to 29.0 mm. Shortly after soil water treatments stipulation, each vase received specific fractions of maximum crop evapotranspiration (ETm) in compliance with water status imposed in our experiment.

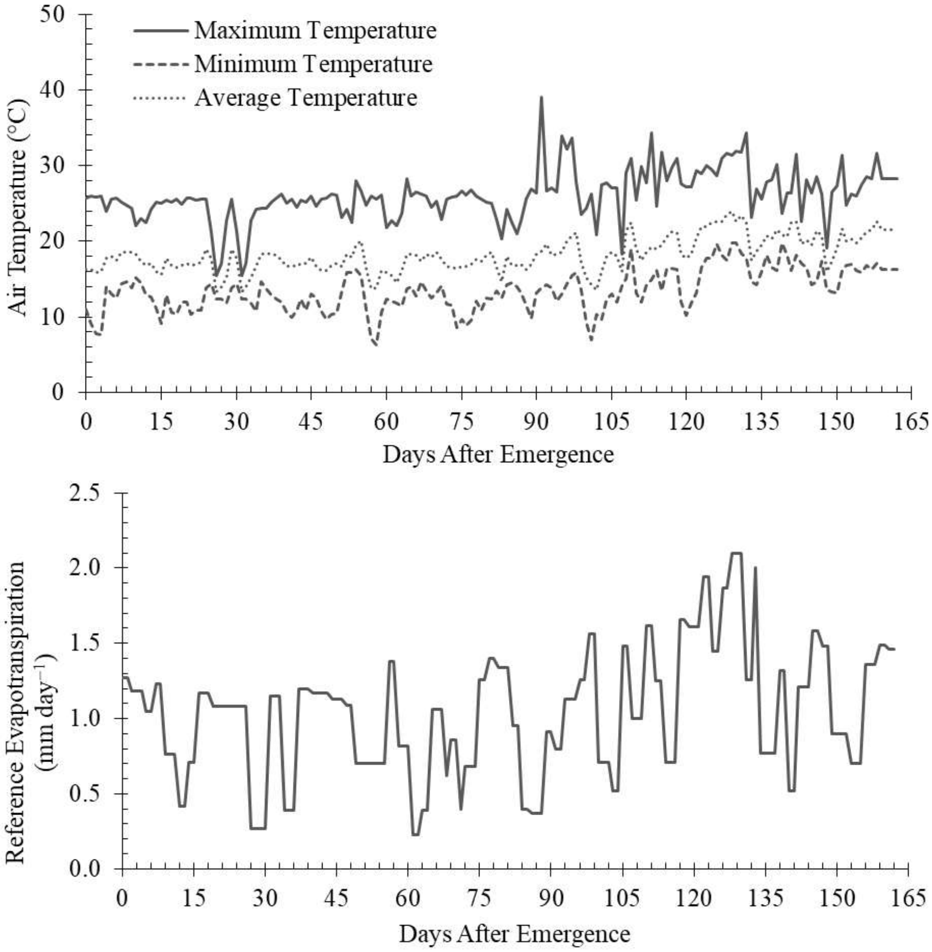

Figure 1. Daily regime of local meteorological elements monitored in a protected environment throughout barley crop growing season, such as: maximum, minimal and mean air temperature (A); reference evapotranspiration (ETo) estimated by the Class A method (B) at Ponta Grossa, PR, Brazil, 2024.

DAE: days after emergence.

As a result of soil water treatments imposition, all vases were irrigated at the following water application rates: 212.3, 176.9, 141.0, and 106.1 mm under 120%, 100%, 80%, and 60% ETm.

Plant height and number of tillers

Plant height was significantly affected by soil water supply levels (Fig. 2), but was not governed by soil Ca:Mg ratios (Fig. 3). Plant height pattern was dependent on soil water status under each soil Ca:Mg ratio treatment. At 1:1 soil Ca:Mg ratio, a quadratic behaviour described crop growth in height as a function of soil water supply, with maximum and minimal values of 56.2 and 48.0 cm under 100% and 60% ETm, respectively. A quadratic regression model for plant height varying as a function of soil water levels was also fitted for 3:1 soil Ca:Mg ratio, with a maximum threshold of 56.7 cm under 120% ETm and of 43.3 cm under 80% ETm. At 6:1 soil Ca:Mg ratio, plant height linearly increased as a function of soil water status, with maximum and minimal thresholds corresponding to 55.4 and 45.6 cm under 120% and 60% ETm, respectively. Conversely, under 9:1 soil Ca:Mg ratio, plant height was not influenced by soil water supply levels.

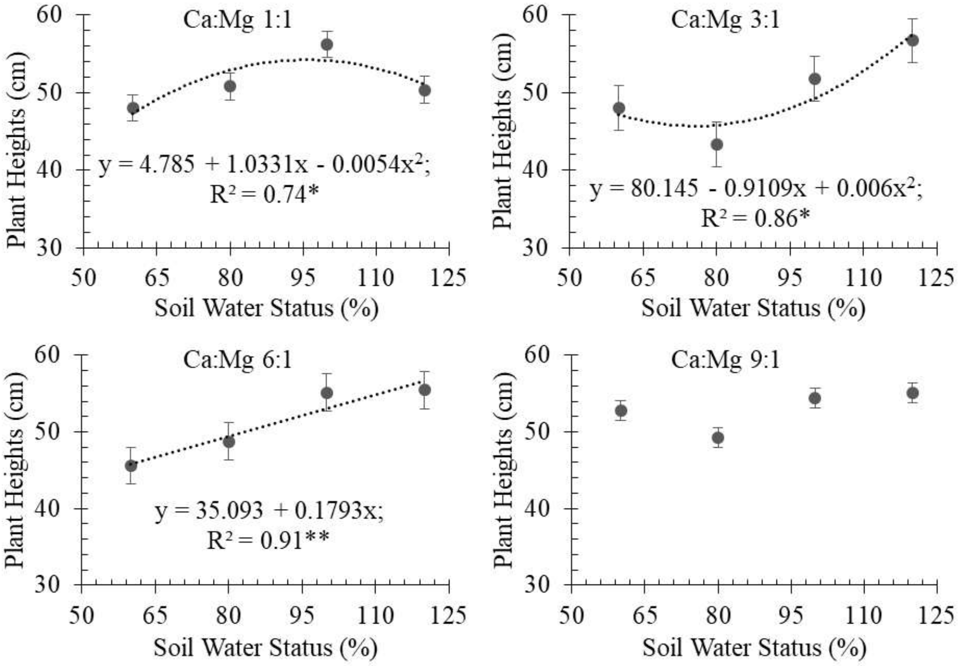

Figure 2. Barley plant height as a function of different soil water supply levels for each soil Ca:Mg ratio under protected environment at Ponta Grossa, PR, Brazil, 2024.
*: $P < 0.05$ and **: $P < 0.01$.

Plant height was significantly driven by soil water levels, however, was not conditioned by soil cationic balance. Such a response-variable presented the highest values under the wettest soil treatment. Similar to the outcomes of our current work, Sanches et al. (2015) came up with a quadratic responsiveness of different soil water levels (50%, 75%, 100%, and 125% ETm) on plant height of three barley genotypes. By examining the impact of three irrigation levels (0, 20, and 40 mm) on four barley genotypes, Mollah & Paul (2011) also detected differences in plant height under field conditions. Its mean values were of 86.1 cm, 81.8 cm, and 74.7 cm under 40 mm, 20 mm, and 0 mm, respectively. Santos et al. (2012) identified effect of water deficit imposed at the beginning of flowering over a 10-day period on wheat genotypes under protected environment. Such studies demonstrated existence of isolate effect of soil water status on agronomic performance of winter cereal crops.

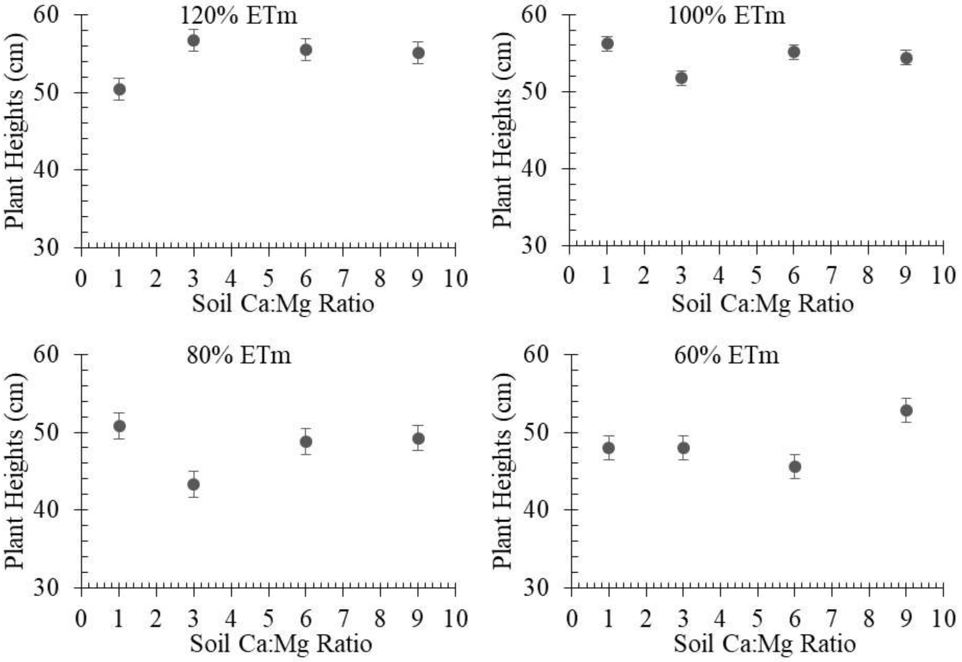

Figure 3. Barley plant height as a function of soil Ca:Mg ratios under protected environment at Ponta Grossa, PR, Brazil, 2024.
*: $P < 0.05$ and **: $P < 0.01$.

The number of tillers per plant of barley was neither significantly affected by soil Ca:Mg ratio nor by interaction effect between water supply and soil cationic balance. Such a response-variable demonstrated a linear increment in the face of rises in soil water availability (Fig. 4). The extreme values of number of tillers oscillated from 4.6 to 7.8 under water treatments of 60% and 120% ETm, respectively.

The number of tillers of barley plants was not influenced by distinct soil Ca:Mg ratios; however, it was governed by soil water status. Such a biological variable linearly increased with increments in soil water supply. A similar result was obtained by Sanches et al. (2015) in light of a linear responsiveness as a function of irrigation water amounts corresponding to 50%, 75%, 100%, and 125% ETm. Mollah & Paul (2011) also found impact of soil water status on number of tillers of barley plants, with mean thresholds of 3.6, 3.3, and 2.8 under irrigation levels of 40 mm, 20 mm, and 0 mm, respectively. The number of tillers per plant of three distinct wheat genotypes under irrigated treatments was higher as opposed to imposition of water deficit from an experiment conducted by Santos et al. (2012). The outcomes reported by the aforementioned authors were quite similar to ours, with mean thresholds fluctuating from 11.4 to 9.6.

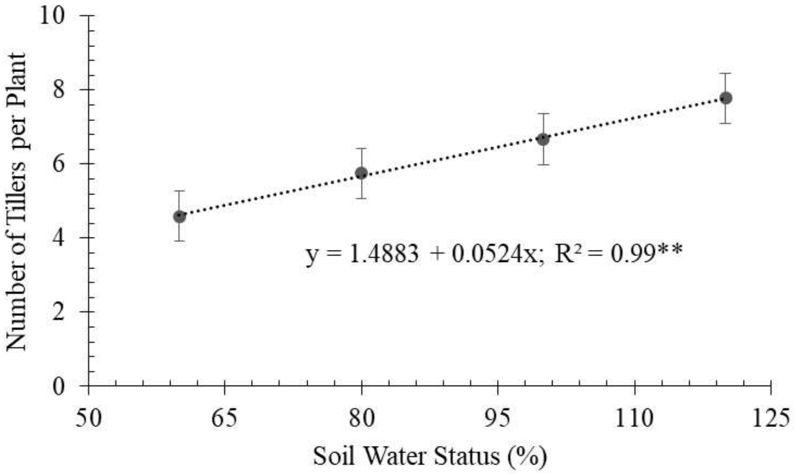

Figure 4. Number of tillers per plant as a function of soil water supply levels under protected environment at Ponta Grossa, PR, Brazil, 2024.
*: $P < 0.05$ and **: $P < 0.01$.

Effect of treatments on crop yield components

NSP was neither considerably conditioned by soil Ca:Mg ratios nor by interaction effect between water supply levels and soil cationic balance. Nevertheless, such a response-variable was impinged upon soil water status (Fig. 5). NSP linearly increased with augments in soil water supply levels. According to the fitted regression equation obtained, the highest threshold was of 5.6 under 120% ETm, whereas the lowest one was of 3.3 under 60% ETm treatment.

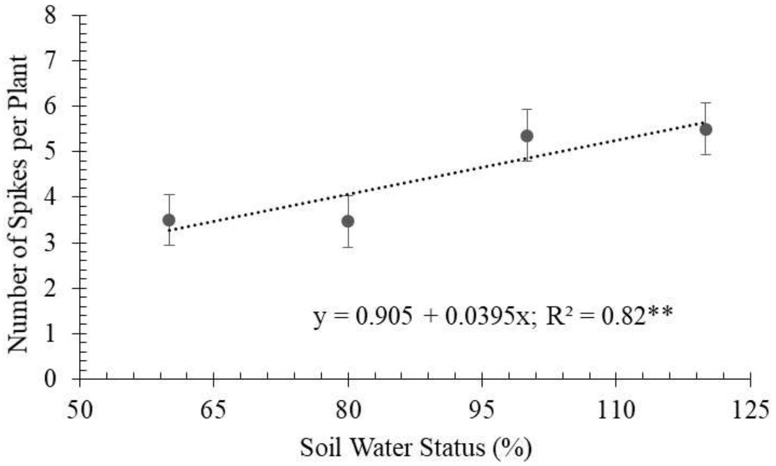

Figure 5. Number of spikes per plant as a function of soil water supply levels under protected environment at Ponta Grossa, PR, Brazil, 2024.
*: $P < 0.05$ and **: $P < 0.01$.

Soil Ca:Mg ratios did not significantly impinge upon NSP. Nevertheless, such a variable was substantially conditioned by soil water supply, being mathematically described by a linear regression model. As in our particular study, number of barley spikes per square meter of soil measured by Nagaz et al. (2008) was affected by soil water supply levels under arid climate of Mediterranean Southern Tunisia. Mean estimated values of NSP were of 219.3, 208.7, 201.0, and 189.3 under 100%, 85%, 70%, and 50% ETm, respectively.

NGP was not significantly governed by soil water supply levels, soil Ca:Mg ratios, and also by interaction effect between both factors. Its mean calculated value was corresponding to 15.2. In the same fashion as to observations for NSP, NGP was neither strongly influenced by soil cationic balance nor by interactions between water supply and soil Ca:Mg ratios; however, NGP linearly increased with rises in soil water availability (Fig. 6). Its extreme values varied from 46.5 to 89.5 under 60% and 120% ETm, respectively.

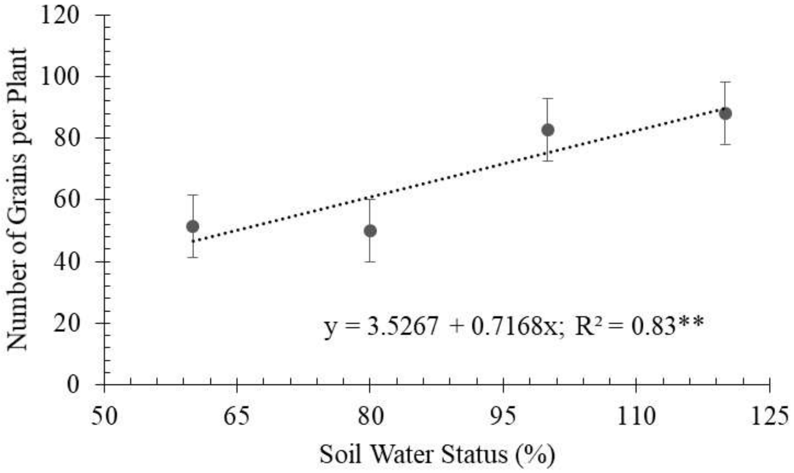

Figure 6. Number of grains per plant as a function of soil water supply levels under protected environment at Ponta Grossa, PR, Brazil, 2024.
*: $P < 0.05$ and **: $P < 0.01$.

NGS was neither determined by soil cationic balance nor by soil water status. However, Sanches et al. (2015) observed a linear increase in NGS as a function of irrigation amounts of 50%, 75%, 100%, and 125% ETm. Different from our observations, Nagaz et al. (2008) found that NGS was governed by soil water status. Mean estimated values of NGS were of 47.9, 46.0, 42.1, and 40.3 under 100%, 85%, 70%, and 50% ETm, respectively. Contrary to our outcomes, Santos et al. (2012) also detected a strong negative impact of soil water deficit on NGS of wheat plants under protected environment.

Soil Ca:Mg ratios did not substantially compromise NGP; however, such a biological variable linearly increased as a function of increments in soil water availability. Similar to our research, Mollah & Paul (2011) verified remarkable effects of soil water status on NGP, with values of 59.3, 52.7, and 46.0 under irrigation amounts corresponding to 40 mm, 20 mm, and 0 mm, respectively. Santos et al. (2012) also evidenced impact of soil water supply levels on NGP of wheat plants grown under a protected environment, with mean thresholds ranging from 629.8 under suitable soil water supply to 376.5 under water deficit condition.

MGP of barley was neither significantly affected by soil Ca:Mg ratios nor by interaction between soil water supply levels and cationic balance, suffering a linear increment as a function of increasing soil water status (Fig. 7). MGP extreme thresholds were of 4.9 g and 2.3 g under the influence of 120% and 60% ETm treatments, respectively.

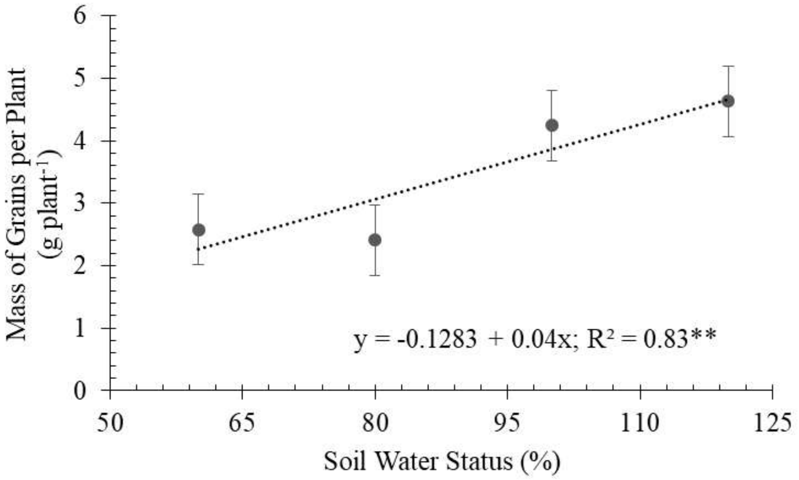

Figure 7. Mass of grains per plant as a function of soil water status under protected environment at Ponta Grossa, PR, Brazil, 2024.

*: $P < 0.05$ and **: $P < 0.01$.

MGP was not influenced by soil Ca:Mg ratios, but a linear augment in such a response-variable as a function of soil water status was verified herein. Similarly, crop yield obtained by Sanches et al. (2015) was also conditioned by soil water supply, being described by a quadratic regression model in light of cultivation of three distinct barley cultivars. As in our work, barley grain commercial yields assessed by Mollah & Paul (2011) were determined by three different soil water regimes. Yields were equivalent to 2.1, 1.9, and 1.7 Mg ha^{-1} under irrigation amounts of 40 mm, 20 mm, 0 mm, respectively. Sanches et al. (2015) also detected reductions in MGP of wheat owing to lack of water at the beginning of flowering. Mean estimated values of MGP were of 5.5 g under suitable soil water supply and 2.2 g under water deficit conditions.

TGW of barley was neither substantially conditioned by soil cationic balance nor by interaction between soil water status and Ca:Mg ratios. Nevertheless, TGW was considerably driven by soil water supply levels. Such a response-variable was mathematically described by a linear regression model that led to maximum and minimal values corresponding to 52 g and 49 g under 120% and 60% ETm, respectively (Fig. 8).

TGW was not affected by soil cationic balance; however, soil water availability exerted a significant effect on expression of such a yield component. By scrutinizing the impact of soil water supply on TGW of three barley cultivars, Sanches et al. (2015) came up with a quadratic relationship between independent variables and response-variables for their studied genotypes. Conversely, Nagaz et al. (2008), as in our study, detected impact of irrigation treatments on TGW of barley grown in open-field conditions at Southern Tunisia. Its mean thresholds gauged by the aforementioned authors were of 48.0 g, 46.7 g, 44.4 g, and 43.2 g under water treatments of 100%, 85%, 70%, and 50% ETm, respectively. In light of evaluation of effect of water deficit on three wheat varieties cultivated under protected environment conditions, Santos et al. (2012) verified that TGW of such a winter cereal was also governed by soil water supply, with mean thresholds corresponding to 35.3 g and 24.3 g under full-irrigation treatment and water deficit imposed at the beginning of flowering, respectively.

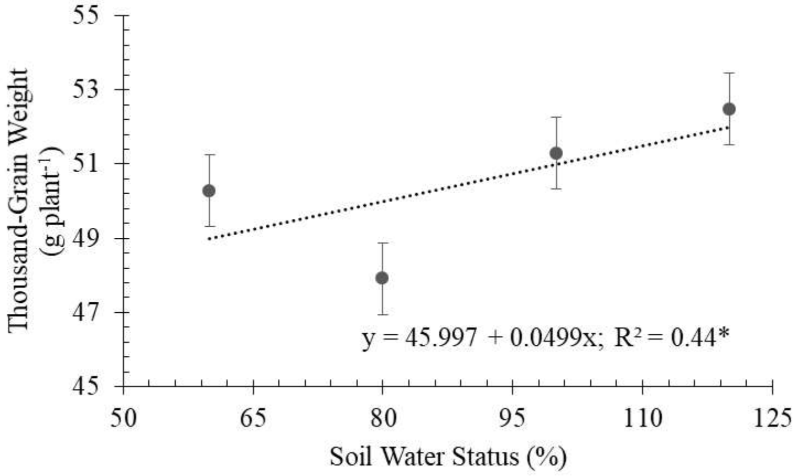

Figure 8. Thousand-grain weight as a function of soil water status under protected environment at Ponta Grossa, PR, Brazil, 2024.
*: $P < 0.05$ and **: $P < 0.01$.

Nevertheless, Medeiros et al. (2008) described a quadratic responsiveness of dry mass of aerial parts of maize plants grown under protected environment for 45 days at different soil Ca:Mg ratios. From such a particular study, the authors verified that dry mass of aerial parts of maize decreased with increments in soil Ca:Mg ratios applied (1:1, 2:1, 4:1, 8:1, 16:1, and 32:1).

Plant water status is dependent on local climatic conditions, as well as irrigation (Vasilaki et al., 2023). In general, crop productivity is a result of rate and duration of effective period of grain filling (Wijewardana et al., 2018). Thus, plants subjected to lack of water throughout such a phenological stage are a target of reductions in size and grain mass (Salinas et al., 1997). According to Shah & Paulsen (2003), lower grain yields under water deficit condition might be ascribed to reductions in photoassimilates synthetized to promote grain filling, limiting absorption of photoassimilates and diminishing duration of effective period of grain filling.

Grain yield turns out to be a consequence of expression and association of several plants' growth components (Anjum et al., 2011). Water deficit culminates in severe reductions in attributes concerning productivity of cultivated agricultural species, likely because of changes in leaf gaseous exchange properties in such a way as to limit plant tissue growth, phloem loading, translocation of assimilates, and dry matter partitioning (Farooq et al., 2009). Several metabolic processes along with activities of different enzymes that play a pivotal role in growth and crop yield are negatively affected by water deficiencies (Allen et al., 1998).

According to Medeiros et al. (2008), increments in soil saturation for Ca^{+2} might bring about nutritional unbalance owing to preferential absorption of such nutrient in detriment of Mg^{2+} and K^+ ions. Deficiency of Mg^{2+} leads to a characteristic chlorosis between foliar nervures, firstly identified in old leaves as a result of a high mobility of this particular ion in the plants (Taiz et al., 2017). With regard to K^+, its deficiency is indicated by a visible symptom as a spot or marginal chlorosis, which evolves to necrosis afterwards more frequent on leaf tips, margins and between nervures. However, such effects were not observed in our study as a function of soil Ca:Mg ratios ranging from 1:1 to 9:1.

Agronomic performance of barley was not governed by soil cationic balance because the soil solution contained suitable Ca^{+2}, Mg^{+2}, and K^+ concentrations, irrespective of those soil Ca:Mg ratios imposed in our study. Such results demonstrated that any Ca:Mg proportion applied to the soil culminated in sufficient amounts of Ca and Mg available to the plants. Supply of Ca, Mg, and K was not conditioned by soil cationic balance to the point of triggering deficiency symptoms of these macronutrients in barley crop.

Soil chemical attributes

Exchangeable Calcium content in soil was significantly affected by both water supply and soil Ca:Mg ratios. However, interaction effect between factors on exchangeable Ca content was not detected in our experiment. There was a linear reduction in exchangeable Ca content with increases in soil water availability, which fluctuated from 5.2 $cmol_c\ dm^{-3}$ under 60% ETm to 4.3 $cmol_c\ dm^{-3}$ under 120% ETm treatments (Fig. 9).

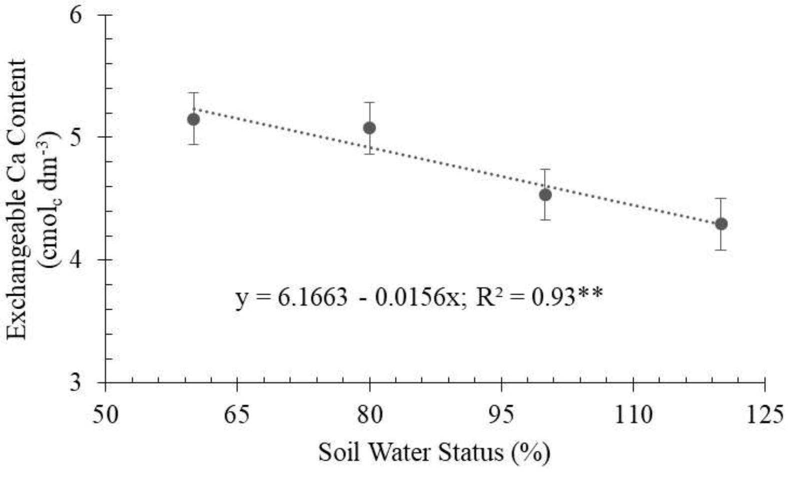

Figure 9. Exchangeable Ca content in soil after barley cultivation as a function of soil water status under protected environment at Ponta Grossa, PR, Brazil, 2024.
*: $P < 0.05$ and **: $P < 0.01$.

Regarding soil cationic balance factor, exchangeable Calcium in soil was described by a quadratic regression model, with maximum and minimal values of 5.3 and 3.7 $cmol_c\ dm^{-3}$ under 9:1 and 1:1 soil Ca:Mg ratios, respectively (Fig. 10).

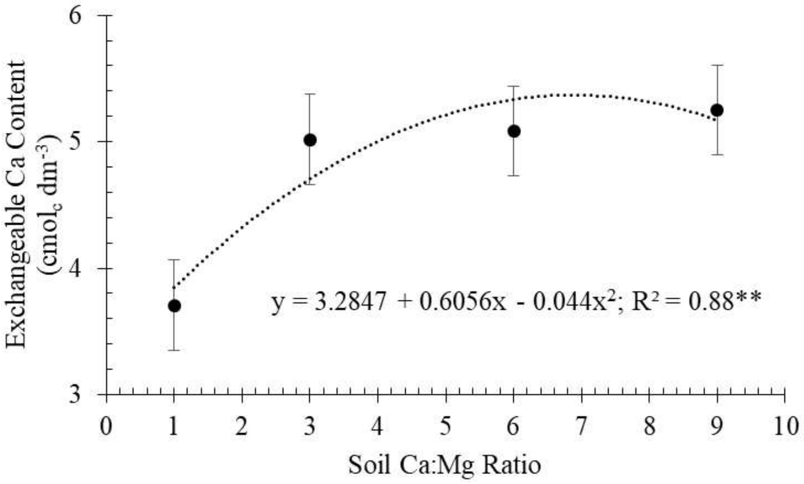

Figure 10. Exchangeable Ca content in soil after barley cultivation as a function of soil Ca:Mg ratios under protected environment at Ponta Grossa, PR, Brazil, 2024.
*: $P < 0.05$ and **: $P < 0.01$.

The increment in soil water supply was conducive to a linear reduction in exchangeable Ca content in soil under the experimental conditions of our study. The greatest soil water status is related to exchangeable Ca concentration in soil in such a manner as to increase Ca uptake in so far as soil moisture turns out be the highest. Absorption of Ca^{2+} by the roots of barley plants was governed by soil water status, demonstrating that the lowest contents of such nutrient were ascribed to the highest Ca^{2+} uptake by the roots, since such a cation gets to the roots by means of mass flux (Raij, 2011).

Increments in soil Ca:Mg ratios also significantly enhanced exchangeable Ca content in soil. This result was already expected and is extremely associated with increases in Ca in soil owing to the highest $CaCO_3$ amounts applied in detriment of the lowest $MgCO_3$ incorporated into the soil as a function of augments in Ca:Mg ratios. Similar to the outcomes reported in our research, Medeiros et al. (2008) detected a quadratic variation in exchangeable Ca contents in soil cultivated with maize as a function of soil cationic balance under protected environment throughout 45 days. Soil Ca:Mg ratios imposed in this experiment were corresponding to 1:1, 2:1, 4:1, 8:1, 16:1, and 32:1 in light of exchangeable Ca contents in soil ranging from 6.2 $cmol_c\ dm^{-3}$ under the lowest Ca:Mg ratio to 24.5 $cmol_c\ dm^{-3}$ under the highest Ca:Mg ratio. Chaganti et al. (2021) found in comparison to control treatment increments in exchangeable Ca contents in soil of 8% and 26% at Hirzel and West Badger, Ohio, USA, respectively, in the face of liming application along with magnesium sulphate throughout 2015–2020 harvest under crop rotation systems of soybean, maize, and winter cereal.

Exchangeable Mg content in soil was neither influenced by water availability nor by interaction effect between water supply levels and soil Ca:Mg ratios. Conversely, exchangeable Mg was extremely determined by soil cationic balance. A quadratic regression model described exchangeable Mg content in soil under different Ca:Mg ratios, with extreme thresholds ranging from 0.5 to 2.2 cmol$_c$ dm^{-3} under 9:1 and 1:1 Ca:Mg ratios, respectively (Fig. 11).

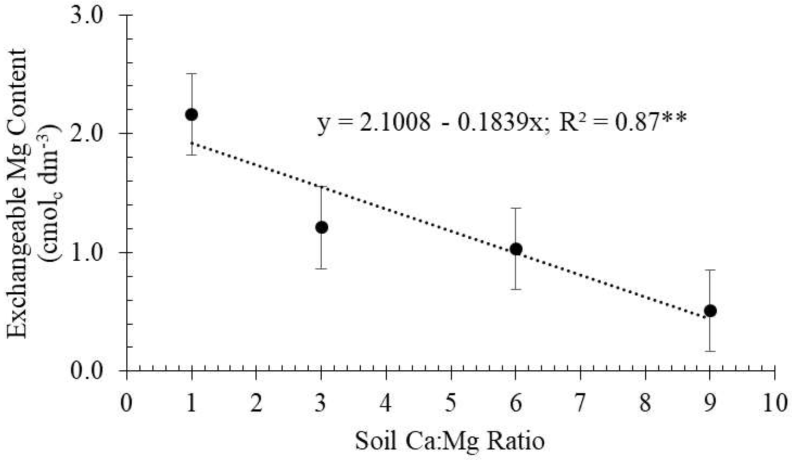

Figure 11. Exchangeable Mg content in soil after barley cultivation as a function of soil Ca:Mg ratios under protected environment at Ponta Grossa, PR, Brazil, 2024.
*: $P < 0.05$ and **: $P < 0.01$.

Similar to evidences found herein for exchangeable Ca contents in soil, a reduction in concentration of Mg in soil was a mere result of increases in $CaCO_3$ quantity in detriment of $MgCO_3$ incorporated as a function of increments in soil Ca:Mg ratios. Likely, Medeiros et al. (2008) observed that exchangeable Mg contents in soil plumbed with increases in Ca:Mg ratios in soil cultivated with maize under protected environment conditions. Their extreme thresholds obtained by the aforementioned authors were of 5.7 and 0.8 cmol$_c$ dm^{-3} under 1:1 and 32:1 soil Ca:Mg ratios, respectively. Chaganti et al. (2021) evidenced increments in exchangeable Mg contents in soil of 27% and 47% at Hirzel and West Badger, Ohio, USA, respectively, as a function of soil cationic balance in the face of liming and magnesium sulphate applications throughout 2015–2020 harvest under rotation systems with soybean, maize, and winter cereal crops.

Soil water supply did not remarkably impinge upon concentration of exchangeable K in soil after barley cultivation (Fig. 12). Furthermore, substantial effects of soil cationic balance and interaction between water supply and soil Ca:Mg ratios on exchangeable K content in soil were not evidenced in our study. Maximum and minimal exchangeable K contents in soil were of 0.27 and 0.16 cmol$_c$ dm^{-3} under 60% ETm and 120% ETm, respectively (Fig. 12).

Figs 10, 11, and 12 evidence that contents of changeable Ca, Mg, and K in soil solution shortly after cultivation of barley were above concentration thresholds recommended by literature concerning liming and soil fertilization techniques for the State of Paraná, brazil

(Pauletti & Motta, 2017). Therefore, as observed in our particular research, Soto et al. (2023) did not detect significant impacts of soil Ca:Mg ratios on soybean and maize yields throughout six harvest seasons in Ohio, USA. Distinct soil Ca:Mg ratios were obtained by the aforementioned authors by application of the following agricultural correctives: calcium sulphate, magnesium sulphate, calcium sulphate + calcitic limestone, and magnesium sulphate + dolomitic limestone. Chaganti et al. (2021) did not detect any impact of applications of calcium sulphate and magnesium sulphate on soybean, maize, and winter cereals yields throughout harvest seasons comprised from 2015 to 2020 in Hirzel and West Badger, Ohio, USA. Such a particular study demonstrated that crop commercial yields were not impinged as a function of the treatments imposed, as long as soil presented desirable levels of natural fertility to provide crops with their nutritional and physiological requirements at a given site.

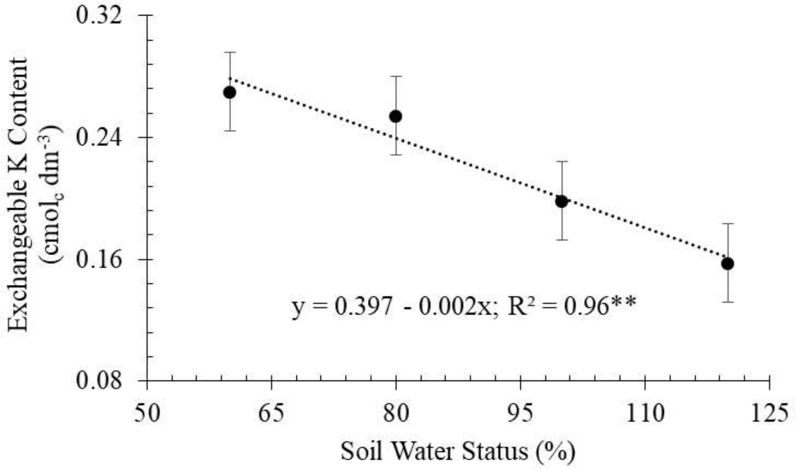

Figure 12. Exchangeable K content in soil after barley cultivation as a function of soil water status under protected environment at Ponta Grossa, PR, Brazil, 2024.
*: $P < 0.05$ and **: $P < 0.01$.

Soto et al. (2023), by conducting field experiments in the USA over 6 years, came up with the conclusion that regression analysis revealed corn yields were positively related to increasing soil pH to optimal levels but were not affected by soil Ca:Mg ratio. Conversely, soybean yields were not related to either soil Ca:Mg ratios nor soil pH. Consistent with previous studies, the aforementioned authors found that balancing soil Ca and Mg levels did not affect corn or soybean yields; however, managing soil acidity remains as a fundamental tool to improve crop yields and manage soil fertility.

The lowest exchangeable K content in soil under wettest soil moisture conditions might be related to the highest soil water availability, which favours K diffusion in soil solution along with its transportation towards rhizosphere. This can also be explained by better nutrient uptake when water is available to plants. Such a discrepancy in exchangeable K content in aerial part of barley plants between irrigated and non-irrigated treatments during periods of three, six and nine days was reported by Anjum et al. (2003).

This particular dynamic of K^+ absorption by the roots is highly driven by soil water status, revealing that the lowest exchangeable K content in soil is a consequence of a higher nutrient uptake by the plants, once the ion-root contact process from soil solution to rhizosphere predominantly takes place by means of diffusion and, at a minor magnitude, by mass flux (Raij, 2011). Both processes in turn are extremely dependent on soil water supply prevailing in agricultural production systems.

CONCLUSIONS

Barley agronomic performance was determined by soil moisture conditions. Increments in the number of tillers per plant, number of spikes per plant, number of grains per plant, mass of grains per plant, and thousand-grain mass were described by a simple linear regression model as a function of increasing soil water availability.

Barley agronomic performance was not conditioned by soil cationic balance because the soil solution contained suitable Ca^{+2}, Mg^{+2}, and K^+ concentrations, regardless of soil Ca:Mg ratios under scrutiny.

Calcium extraction by barley plants linearly augmented as a function of increasing soil water availability regimes.

Magnesium extraction by barley plants linearly plummeted with rises in soil water availability under 3:1, 6:1, and 9:1 soil Ca:Mg ratio treatments.

Soil Cationic balance did not affect extraction of calcium, magnesium, and potassium by barley plants.

Soil cationic balance did not impinge upon nutritional state of barley plants irrespective of soil moisture status.

Assessment of soil Ca:Mg ratios to maintain food security and other ecosystem services ranging from 1:1 to 9:1 does not guarantee either fertilizer or limestone use efficiency in order to substantially minimize production costs at a commercial scale in barley fields.

The most suitable soil Ca:Mg ratio for obtaining the best agricultural response of barley under a protected environment did not depend on soil moisture levels.

Additional studies are needed to further promote a better understanding on crop physiological mechanisms in light of distinct root cation exchange capacity (CEC) as a function of plant metabolism type, which certainly govern both water dynamics in the soil-plant system and also uptake efficiency of Ca, Mg, and K in agricultural production fields.

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