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Broadcast nitrogen application can negatively affect maize leaf area index and grain yield components under weed competition

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ABSTRACT

Nitrogen (N) application and weed control play critical roles in the development of crops. In maize (*Zea mays* L.) cultivation, surface broadcast N application aiming at higher productivities is a common practice. However, N addition under weed competition could promote weeds rather than maize. To investigate this, a field study was developed over a Brazilian eutric nitisol for summer maize. We manipulated the presence (+) or absence (−) of surface broadcast N fertilization (N_S) at the recommended dose (90 kg ha^{-1} N) and weed control (W_C), obtaining the treatments N_S+W_C+, N_S+W_C-, N_S-W_C+, N_S-W_C-. We aimed to determine 1) whether maize could profit from N application even under weed competition, and 2) how treatments would affect maize's leaf area index and all grain yield components (cobs $area^{-1}$, rows cob^{-1}, grains row^{-1} and individual grain weight). We hypothesized that broadcast N application could jeopardize maize productivity by favoring weed development. Under no weed control, N application increased weed biomass by ~58%, which resulted in reductions of 57% in leaf area index, 6.9% in rows per cob, 48% in grains per row, and 18.7% in grain weight. Ultimately, the grain yield (8216 kg ha^{-1}) of the best performing treatment (N_S+W_C+) was 66% higher than that with the worst performance (N_S+W_C-), of 2797.3 kg ha^{-1}. We conclude that in fertilized areas, weed control should be a priority, since the N applied under weed competition could be detrimental to maize's leaf area index, and affect most yield components and overall productivity.

1. Introduction

Maize (*Zea mays* L.) is a key crop for Brazilian agriculture, occupying over 4.5 million ha in the summer season of 2021/2022 (CONAB - Companhia Nacional De Abastecimento, 2022). While productive farms in the country can average yields as high as 12000 kg ha^{-1}, the average summer maize productivity was 5501 kg ha^{-1} in the same period (CONAB - Companhia Nacional De Abastecimento, 2022). These numbers indicate the existence of significant yield gaps at many production sites, which can be attributed to suboptimal temperatures, water availability, unsuitable genotype choices, low soil fertility and nutrient input levels, and weed competition (Andrea et al., 2018).

The productivity (kg ha^{-1}) of maize is collectively determined by its grain yield components (GYCs). These are the number of cobs per area, number of rows per cob, number of grains per row and individual grain weight. Numerous factors can influence the GYCs of maize (Sah et al., 2020), with specific phenological stages playing critical roles in determining the potential of each GYC individually (Abendroth et al., 2011; Ciampitti et al., 2016). Stresses during these periods can lead to reduced yields, posing a significant threat to commercial production.

To enhance the expression of maize's GYCs and its overall productivity, management strategies focus on providing adequate water and nutrients, minimizing competition with weeds, and mitigating damage caused by insects and diseases that can affect the plant's leaf area index (LAI) and photosynthetic capacity. While maximizing GYCs leads to increased productivity, the maize's LAI should be optimized, because

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vegetative growth requires considerable resources. Under weed competition intraspecific shading, competition for water and nutrients etc. can ultimately reduce the efficiency of the plant's photosynthetic apparatus, resulting in lower yields.

Aiming at high productivities, nitrogen (N) is typically applied in the furrow before sowing. Additional N supply is commonly done through surface broadcasting fertilizers between V4 and V8 (four to eight fully extended leaves) to supply the plant's demand and achieve competitive yields (Pöttker and Wiethölter, 2004). Moreover, effective weed control is also a crucial challenge for attaining high grain yields in maize (Venkataraju et al., 2022). Implementing a comprehensive weed management strategy helps farmers ensure that the crop is not hindered by competition with undesired plant species. Failure to efficiently control weed growth can result in yield reductions reaching up to 85%–90% (Vidal et al., 2004; Galon et al., 2010). Weeds compete with cash crops for essential resources such as water, nutrients, light, and space, and can significantly interfere with maize's wind pollination, leading to barren ears and unfertilized ovules, ultimately reducing grain yield (Cerrudo et al., 2012).

Both N fertilization and weed management can be complex practices. Recent studies have addressed difficulties and uncertainties in the best timing for N application in crops (Abera et al., 2020; Mosisa et al., 2022). Likewise, weed control strategies can vary depending on factors such as maize variety, weed species present, plot size, region, growth season, soil type, budget, availability of products and implements, and technical support. Such nuances make it challenging to consistently achieve weed-free production areas, particularly for small-scale farmers with limited resources and technology. In such conditions, farmers may still perform surface N application in the hopes of improving maize performance, and in the process, might be further jeopardizing their yields.

This study holds importance as it investigates the interplay between N fertilization and weed management on maize production. To that end, we conducted a field experiment in a highly fertile clayey eutric nitisol in Brazil. By manipulating the presence (+) and absence (−) of the factors 1) surface broadcast N application and 2) efficient weed control, we aimed to assess the individual impact of each factor as well as their interaction on maize's LAI and GYCs. We hypothesized that weed species might have a greater propensity to benefit from broadcast N application compared to maize, thereby potentially compromising maize's LAI and all GYCs and rendering the practice ineffective.

2. Material and methods

The experiment was conducted between 11th of September 2018 and the 1st of January 2019 (113 days) in a grassland plot (22°42'13"S, 47°38'07"W) with total area of 560 m^2 (14 m × 40m) located in Piracicaba – São Paulo, Brazil. The soil is a clayey eutric nitisol (WRB Working group, 2014). Prior to establishment, soil chemical and physical analysis were carried out, and a compaction assessment was performed at field capacity by determining soil's resistance to penetration with a penetrometer (model Hatô - Mafes) in 15 random points for each depth. This data can be seen on Table 1.

Various authors have suggested soil pressure thresholds for root growth, varying from 2 MPa (Taylor and Burnett, 1964; NeSmith et al., 1987) to 3.5 MPa (Merotto and Mundstock, 1999). Since no pressures higher than 1.1 MPa were obtained in our analysis at all depths, soil compaction was considered to have minimal impact on root growth. Therefore, the plot was mechanically plowed to kill the weeds and furrows were created for sowing. At this time, an irrigation system consisting of 3 cannon sprinklers that covered the whole experimental area was installed, guaranteeing water supply through the cycle.

2.1. Climatological data

Climatological data series was collected by the automatic weather station of the Department of Biosystems Engineering of the Luiz de Queiroz College of Agriculture - University of São Paulo, located <2 km away from the experimental plot. The data on daily average, maximum and minimum temperature, as well as precipitation during the maize cycle can be seen in Fig. 1. The average temperature for the whole period was 23.4 °C, while maximum and minimum were 35.5 °C and 12.2 °C, respectively, within the limits for maize production (Ramirez-Cabral et al., 2017). During the 113 days of the experiment, the plots received a total of 511.3 mm of cumulative precipitation. To supply the maize's water requirements, 16 mm of irrigation was performed upon sowing on September 11th to stimulate emergence. Five additional 24 mm irrigations were performed on September 25th, October 22nd and 30th, December 5th and 10th, for a total of 647.3 mm of water supplied during the maize's cycle, within the range of maize's requirements (Bergamaschi et al., 2001). The ideal weather conditions experienced during the maize growth prevented undesired climatic interferences in its cycle, allowing treatments to be the only factor affecting maize development.

2.2. Base fertilization and sowing

The maize hybrid used in the experiment was the P4285YHR (Pioneer®), requiring 865 growing degrees (GD) for flowering and 1615 GD to reach maturity, categorizing it as an early variety. The target population was 55555 plants ha^{-1}, with spacing of 45 cm between lines and 40 cm between plants.

Before sowing, base fertilization was manually performed adhering to the recommendations of the Boletim Técnico 100 (Raij et al., 1997) for maize cultivation in the state of São Paulo. For our soil fertility class, the application of 30 kg ha^{-1} of N and K, and 50 kg ha^{-1} of P is recommended. To achieve this, 300 kg ha^{-1} of an NPK (10-10-10) formulation was applied into the furrow, supplemented with 44 kg ha^{-1} of triple superphosphate. Finally, the applied fertilizer was carefully covered with soil using a hoe for optimal incorporation. The sowing of maize was manually performed on the 11^{th} of September 2018, with double seeds being placed at 4 cm depth to improve plant uniformity. Emergence took place on the 18th of September, and plants were thinned on the 24th of September, achieving the desired final population.

2.3. Treatments

While the whole experimental plot received the same base fertilization, treatments were established by manipulating the presence (+) or absence (−) of the factors 1) Additional N application (N_S) at growth stage V4 (manually broadcast onto the soil surface) and 2) Manual weed control (W_C), keeping the area free of competition. This resulted in four treatments, representing maize grown in the hypothetical scenarios with a) additional N application and weed control (N_S+W_C+), b) additional N

Table 1
Soil chemical and physical characteristics per depth prior to experiment establishment.

Depth cm	pH_{CaCl2}	O.M.	P_{Resin}	K^+	Ca^{2+}	Mg^{2+}	CEC	V	Compaction	Clay	Silt	Sand
		g kg^{-1}	mg kg^{-1}	$mmol_c$ dm_{-3}				%	MPa	g kg^{-1}		
0–10	5.0	24	24	4.5	38	11	68.5	78	0.9	406	227	367
10–20	5.0	20	19	4.1	39	12	68.1	81	1.1			
20–40	5.3	14	15	3.0	40	13	69.0	81	1.0			

Abbreviations: O.M., organic matter; SB, sum of bases; CEC, cation exchange capacity; V, base saturation.

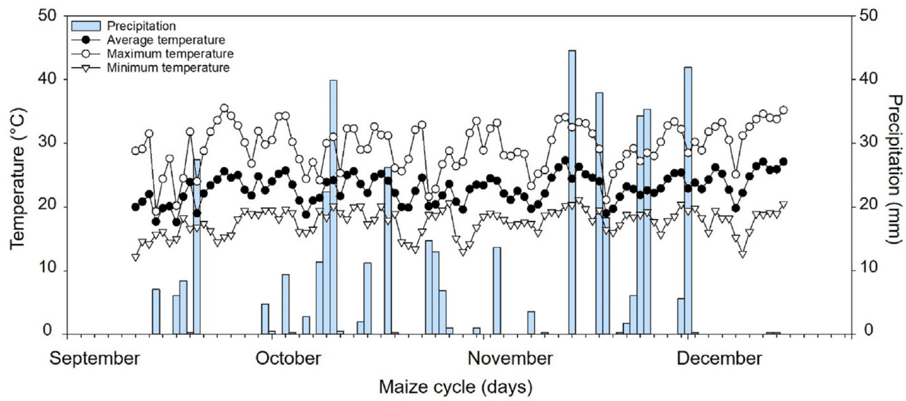

Fig. 1. Average, maximum, and minimum temperature (°C) and precipitation (mm) during the maize cycle based on the climatological data series collected in the city of Piracicaba (São Paulo, Brazil) by the Department of Biosystems Engineering of the Luiz de Queiroz College of Agriculture - University of São Paulo.

application and no weed control (N_S+W_C−), c) no additional N application and weed control (N_S−W_C+), d) no additional N application and no weed control (N_S−W_C−). Each treatment was replicated five times (n = 5), and replicates were randomly allocated in the experimental area through blocks in a factorial experimental design. Blocking was performed to reduce the variability of soil chemical, physical and biological parameters, as well as weed species distribution in the plot.

The W_C+ treatments benefitted from 5 weed removals throughout the cycle, performed by hoeing the undesired species. The events took place on 18th of September (7 days after planting, DAP), 1st of October (20 DAP), 12th of October (31 DAP) and 22nd of October (41 DAP). After weeds were hoed, their biomass was left on the soil surface. The N_S+ treatments were fertilized on the 5th of October, when the maize was in phenological stage V4. At the occasion, 90 kg ha^{-1} of N were broadcast onto the soil surface, using a mix of 70% urea ($CO(NH_2)_2$) coated with the urease inhibitor N-(n-butyl)-thiophosphoric triamide (NBPT) and 30% conventional urea. This was done due to the higher efficiency of NBPT coated fertilizers, in the intention to reduce N losses to the environment (Cantarella et al., 2018).

2.4. Sampling and analyses

At 60 DAP (pre-flowering), 25 random plants from each replicate (avoiding border rows) were collected for determination of total leaf area using a leaf area meter (model LI-3100C, LI-COR). The mean leaf area (m^2) of the 25 plants was then multiplied by the plant population in each replicate, and divided by its area, thus being converted to LAI (unitless) through the equation (1):

$$LAI = \frac{\text{Leaf area } (m^2)}{\text{ground area } (m^2)} \quad (1)$$

At 113 DAP, 25 random maize plants per replicate were harvested to determine number of cobs per m^2, number of rows per cob, number of grains per row and individual grain weight using a precision scale. Grains were husked with the aid of a mechanical maize kernel remover. Three subsamples of fresh grains per treatment were milled at 2 mm, weighed for fresh weight, and oven-dried for 48 h at 70 °C. Grain humidity was 15.5% and was calculated as the difference in weight between fresh and dry samples.

At the same moment, 5 m^2 from each replicate in the field were randomly selected using a 1 m × 1 m wooden frame, repeating the process 5 times per replicate. All the weeds' shoot within the selected area was collected, dried in an oven at 70 °C for 48 h and weighed to determine mean dry shoot biomass (DSB) production per m^2.

2.5. Statistical analysis

Differences between means for all variables were determined through the Kruskal-Wallis test using 5% (α = 0.05) as the cut-off for statistical significance. Means were compared through the confidence intervals at 95% confidence level, represented by the error bars in the charts. If there is an intersection between two intervals (error bars), we conclude that the means are not significantly different. Otherwise, there is evidence of a significant difference between means. All analysis were performed using RStudio version 4.2.2.

3. Results

3.1. Weed species and dry shoot biomass production

The most important weed species identified in the area were *Sorghum halepense* (L.) Pers., *Amaranthus viridis* L., *Raphanus raphanistrum* L., *Cyperus rotundus* L., and *Alternanthera tenella* (L.) P. Beauv. Other plant species were present, but in small numbers. No particular distribution of weed species was observed in the experimental plot (absence of concentration of the same species, patches or clumps), which resulted in the same species producing similar biomasses across replicates.

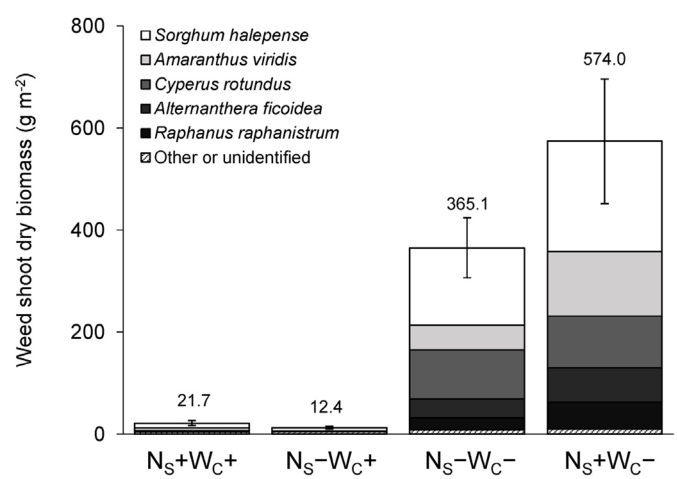

Fig. 2. Average shoot dry biomass (g m^{-2}) of different weed species found in the experimental area after the maize cycle as affected by each treatment. Values on top of the bars represent the means of the total weed shoot dry biomass for each treatment. (n = 5). Bars represent confidence intervals for the total weed biomass at 95% confidence level. N_S = surface N application; W_C = weed control. Presence and absence are represented by + and −, respectively.

The mean DSB of the weeds (g m^{-2}) discriminated by species as affected by each treatment after the maize cycle can be seen in Fig. 2. In the treatments in which weeds were not removed (W_c-), N addition resulted in an average DSB ~58% higher than under no N application. It is worth noting that even on the W_C+ treatments, low weed DSB was still present, although unlikely to have negatively impacted maize productivity.

3.2. Maize leaf area index, grain yield and its components

Both surface N supply and weed control significantly affected maize's LAI, all GYCs (except for number of cobs per m^2) and total grain yield. The results for each of these parameters are displayed in (Fig. 3).

All treatments differed among themselves for LAI and grain yield. No differences in number of cobs per m^2 were found between any treatments. For all other GYCs, significant differences were found between the worst-performing treatment (N_S+W_C-) and all other treatments. Compared to the best-performing one (N_S+W_C+), the former had losses of 6.9% in rows per cob, 48% in grains per row, and 18.7% in grain weight. Within the W_C+ treatments, the N_S- produced LAI and yield that were 20% and 30% lower, respectively, when compared to the N_S+. Interestingly, surface N application had a negative effect in the LAI and yield of the weed infested treatments. Such treatments also exhibited signs of N deficiency (namely thin stems, pale-green leaves, and stunted growth) regardless of receiving N application or not. No N deficiency symptoms were observed in neither W_C+ treatment. Under no weed control, surface N addition caused a LAI and grain yield reduction of 24 and 41%, respectively, while great reductions of 57% for LAI and over 66% in yield respectively were seen in comparison to the N_S+W_C+. Furthermore, high correlation was found between maize's LAI and grain yield, as seen in Fig. 4.

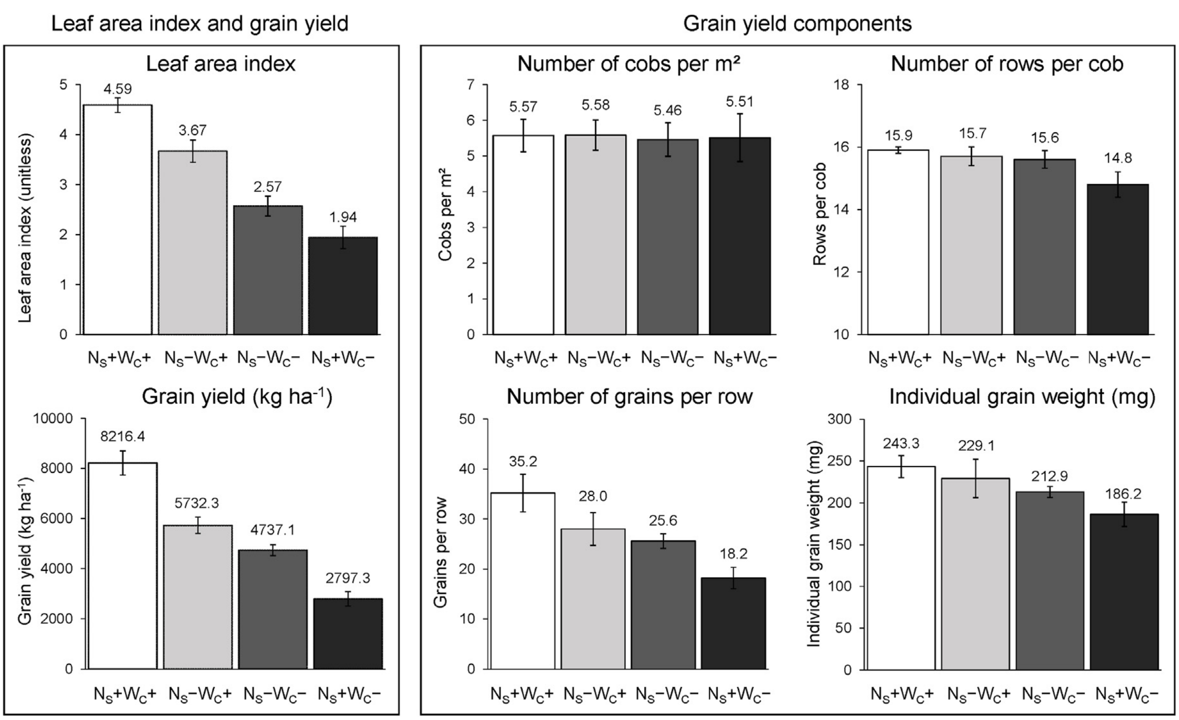

Fig. 3. Maize's leaf area index, grain yield, and grain yield components (cobs per m^2, rows per cob, grains per row and individual grain weight) as affected by the presence or absence of surface nitrogen application and weed control. Values over the bars represent the replicates' means (n = 5). Bars represent confidence intervals at 95% confidence level. N_S = surface N application; W_C = weed control. Presence and absence are represented by + and −, respectively.

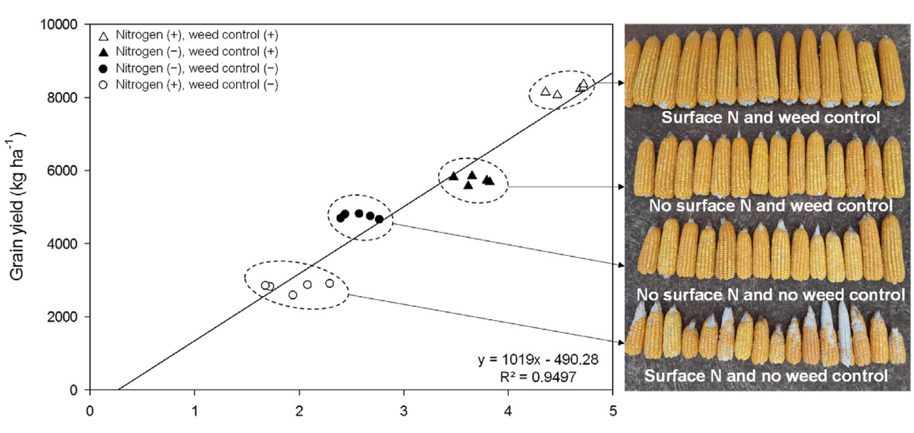

Fig. 4. Correlation between maize's leaf area index (unitless) and grain yield (kg ha^{-1}) under presence and absence of weed control and broadcast nitrogen application (n = 5).

4. Discussion

Most weed species encountered in the experimental area hold considerable importance for Brazilian agriculture and/or maize production specifically. For instance, *S. halepense* and *C. rotundus* have been reported to be two of the most important weeds in maize, the former being potentially responsible for yield losses of up to 100% (Holm et al., 1977; Vasilakoglou et al., 2005). Furthermore, *A. viridis* is a widespread weed in farmland throughout the whole country, and, along with *A. tenella* cause losses not only in maize, but also other crops (Lorenzi and Matos, 2002; D'Amico-Damião et al., 2020). The exceptional DSB productions seen in our experiment were achieved by creating an extreme hypothetical scenario that deliberately favoured weed growth and development at the expense of maize growth in the treatments with no weed control. Weed species possess remarkable adaptability to their environments, employing a diverse range of strategies to maximize their success and competitive advantage over other plant species (Adeux et al., 2019; Sharma et al., 2021; Neve and Caicedo, 2022). These strategies often involve efficient resource utilization, including water, nutrients, light, and carbon, leading to rapid development. Moreover, weeds employ various methods of dissemination, such as producing a significant number of seeds that can be spread through self-seeding, wind, animals, and water. Additionally, they can reproduce through the production of rhizomes, bulbs, stolons, tubers, and corms (Zimdhal, 2018).

Although weeds might be adapted and even thrive on restraining environments, they may also benefit from the management practices performed to favor cash crops, such as soil tillage, fertilization, irrigation etc. (Balasubramanian and Palaniappan, 2004). Such practices allow the weeds to develop quickly, spread and explore a higher soil volume than the maize due to their higher population. In our experiment, despite the naturally high soil fertility and the relatively high soil organic matter levels for tropical soil standards (often associated with N availability), surface N application had a substantial impact in plant growth, benefitting the maize plants under W_C+ and the weeds under W_C-.

The competition between weeds and maize resulted in reductions in LAI, GYCs and ultimately yield for all treatments not contemplated by at least one of the factors. The underlying mechanisms behind such losses can be analyzed through ecological and physiological lenses. From an ecological perspective, preemptive competition results in yield losses by reducing the availability of nutrients, water, light, space, etc. (Neve and Caicedo, 2022). Furthermore, weeds can also exude allelopathic substances (soil-borne and/or volatile chemicals) which can impair the germination and development of neighboring plants. However, although limiting resource availability can lead to physiological consequences, the presence of weeds has been shown to reduce crop's yield regardless of competition for resources (Horvath et al., 2023). Rajcan and Swanton (2001) have shown that weeds can affect maize plants not only through direct competition, but also by altering early developmental trajectories, promoting changes in light quality and prompting stress responses, all of which may impact overall development.

An intricate assessment of the mechanisms behind weed-related productivity losses in maize was presented by Cerrudo et al. (2012), who showed that early competition can reduce maize's growth rate and dry biomass production, as well as canopy development and structure. Being generally considered a high-input crop, maize requires significant amounts of resources to achieve substantial yields. In terms of nutrition, N is particularly impactful, as it contributes to protein synthesis, chlorophyll production, leaf expansion, lateral bud growth and overall dry biomass, and has been shown to be required in the order of over 20 kg of N to produce 1 ton of grain (Galindo et al., 2019). In the Brazilian state of São Paulo, recommended N doses can vary from 20 to 170 kg ha^{-1} for summer maize (Raij et al., 1997), contributing to plant establishment, development, greater LAI, and ultimately higher yields, even in highly fertile soils.

The LAI is intimately related to the photosynthetic capacity of plants, as well as respiration and evapotranspiration, all of which influence grain yield (Gower et al., 1999). However, increased LAI does not necessarily result in higher yields. This is because producing vegetative structures (such as leaves) requires significant resources. However, if the fraction of photosynthetic active radiation intercepted (fPARi) by the plants is suboptimal, these resources may not be used efficiently, which could negatively affect yields (Drewry et al., 2010; Srinivasan et al., 2017). Shading conditions caused by excessive crop population density (intra-crop shading), inadequate leaf architecture and/or competition with weeds (weed shading) can significantly reduce fPARi and, consequently, photosynthesis. This results in significant losses in plant biomass, GYCs and grain quality (Earley et al., 1966; Jia et al., 2011; Yuan et al., 2021). In this sense, optimizing LAI (rather than maximizing) is crucial to promote the efficient use of available resources and ultimately obtain higher yields.

To achieve optimal LAIs, adequate N supply is paramount. In our experiment, N deficiencies observed exclusively in the W_C- treatments indicate that when grown in weed-free conditions, maize plants managed to take up sufficient N from the soil to avoid apparent deficiency symptoms. However, preemptive competition with weeds resulted in lower N availability for the maize (in both fertilized and unfertilized treatments), considerably impacting their LAIs and, consequently, net photosynthesis. Another interesting aspect is that the increase of crop's LAI linked to adequate N supply can reduce the quantity and quality of the light reaching low into the canopy. This impairs weed establishment, growth and growth speed, ultimately allowing maize to outcompete the weeds which may germinate later in the cycle (Teasdale, 1995).

Stunted growth, losses in biomass and in LAI will impact maize's GYCs, which are determined in different phases of maize's development (Andrade et al., 1999, 2002; Cerrudo et al., 2013, Bă̦sa et al., 2016). Maize's phenological stages are commonly divided into 1) vegetative, comprised of VE (emergence) and all V*n* (*n* completely extended leaves) stages and 2) Reproductive, VT (tassel visible) ranging from R1 (silking), R2 (grains filled with clear liquid) until R6 (physiological maturity) (Neeser et al., 2004). Stresses in each of these stages can compromise different GYCs, negatively affecting productivity, and can be related to the availability of resources, weather conditions, plant health, competition with weeds, allopathy, etc. The moment of definition of each GYC can be seen in Fig. 5.

In our experiment, we estimate that the differentiation between treatments effectively started approximately at the phenological stage V4 (20 DAP), coinciding with the surface N application and with the beginning of the critical period of competition for maize, comprehended between V2 and V12 DAP, depending on maize variety and production system (Tursun et al., 2016). This means that neither weed competition nor additional N supply had affected the plants before V4. Interestingly, the number of cobs per area was the only component that did not differ significantly among treatments, since it is defined between VE and V4 (before treatments effects).

In the hypothetical scenarios created in our experiment, three major consequences of inadequate weed control on maize can be highlighted. Firstly, the interspecific competition compromised the availability of light and nutrients for maize plants, negatively affecting its yield components. Secondly, this competition rendered N surface fertilization not only ineffective, but detrimental, since weeds exhibited a remarkable ability to utilize resources, producing substantial biomass, as observed on treatment N_S+W_C- (Fig. 2). Lastly, the abundance of weed biomass posed a potential barrier for wind-mediated maize pollination (anemophily), obstructing the transfer of pollen to female flowers. On top of this, Cerrudo et al. (2012) showcased that early weed competition can increase the anthesis-silking interval, that is, the amount of time between the onset of pollen shed (anthesis) and the development of silks (female reproductive structures), which should occur in synchrony under optimal conditions.

This is the case because weed competition can affect several parameters such as density of plants in the field, humidity and temperature in the canopy, resource availability (water, light, nutrients), as well as

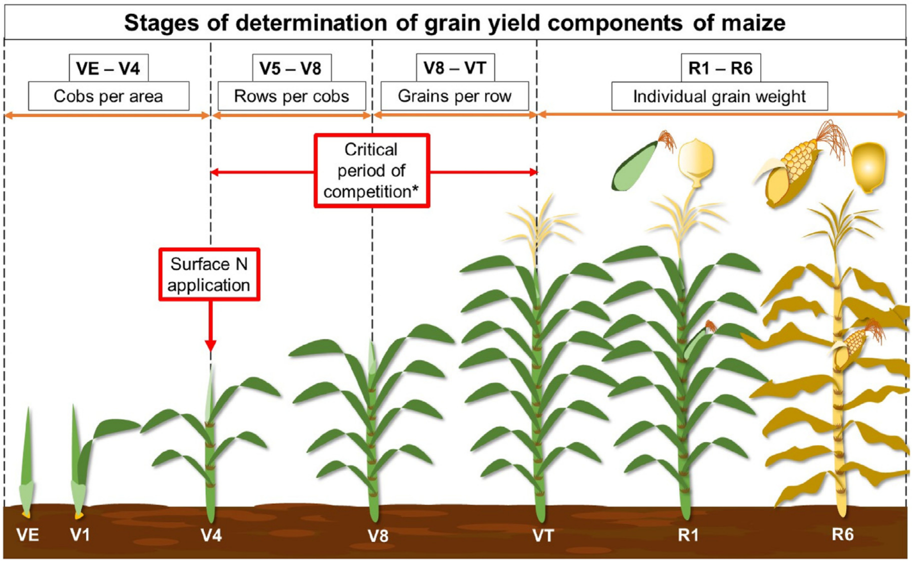

Fig. 5. Maize phenological stages for the determination of grain yield components. Vegetative stages start at VE, with coleoptile emergence and elongation. V1 is characterized by one fully extended leaf, increasing by one extra leaf at each subsequent vegetative stage. VT indicates the visibility of the last branch of the tassel. From then, reproductive stages go from R1, with visible silks outside the husk, followed by R2, with "blister-like" kernels. From then on, reproductive stages describe the maturation of the kernels until reaching physiological maturity at R6, with kernels reaching maximum dry weight. *The critical period of competition in the region is usually between 20 and 60 days after planting. In our study, these dates coincided with the phenological stages V4 and VT for most plants. Adapted from Neeser et al., 2004).

exudate compounds which may impact maize's growth and development, ultimately affecting the anthesis-silking interval (Bolaños and Edmeades, 1996; Silva et al., 2022). Combined, these obstructions can potentially result in a significant number of unfertilized ovules and consequently impact yield. Guaranteeing sufficient nutrient and water availability for maize, using recommended plant populations in agreement with edaphoclimatic conditions and minimizing weed competition are among some of the management practices which can reduce the anthesis-silking interval, enhancing pollination and potentially yield.

The extreme conditions promoted by our experimental setup serve as a poignant reminder that although complete disregard for weed control is unlikely to happen in a real production scenario, the application of nutrients and water aimed at cash crops might still be intercepted by weeds at varying proportions depending on infestation rates. This evidences that failing to effectively control competing species has the potential to reduce the efficiency of multiple management practices such as fertilization and irrigation, which could explain unsatisfactory yields obtained by numerous farmers in Brazil despite significant investment.

Our results corroborate those of Kazmi (1993), who reported that weed competition reduced the number of grains per cob, 1000-grain weight, and grain yield of maize. Likewise, Mukhtar et al. (2007) reported yield losses between 67% and 79% for summer maize when under unrestricted weed growth. Suboptimal N supply has also been shown to affect number of grains per cob (Paponov et al., 2005) and individual grain weight (Hisse et al., 2019), while Monneveux et al. (2005) considered grain abortion as the most impactful component in defining yields under inadequate N availability. In our experiment, weed competition interacted with N application, which significantly increased weed DSB and intensified their competition mechanisms, such as the dispute for nutrients (especially N), water, light (quality and quantity), space, higher root density and volume of exudates among others, all of which contributed to losses in GYCs (except cobs area^{-1}), with number of grains per row being the most impacted (percentage-wise).

Our study has provided insights into the detrimental effects resulting from the interplay between weed infestation and N application in maize, highlighting the severity of the damages. However, there is still much to uncover regarding this complex relationship. This study was limited inasmuch as it did not explore different N doses, methods and timing of application, sources, nor weed infestation rates or several other important species for tropical environments. Furthermore, as only one agricultural year was investigated here, further long-term studies may be helpful to assess the consistency of the reported results, ensuring they are replicable under different edaphoclimatic conditions over longer time spams. Additional research encompassing a broader range of N doses and application methods, along with exploring different levels and timings of weed control, could contribute to enhancing our under-standing of maize's yield components and how stresses in different stages of development may affect them. Such studies have the potential to make significant contributions toward bridging the yield gaps currently observed in Brazilian maize production.

5. Conclusions

Our study revealed that in the absence of weed control, surface N application (90 kg ha^{-1} N) resulted in an increase of weed's biomass, from 365.1 to 574.0 g m^{-2}, which led to reductions of up to 57% in maize's leaf area index and 66% in grain yield, which ranged from 2797.3 kg ha^{-1} for the worst performing treatment (N addition and no weed control) and 8216 kg ha^{-1} for the best performing treatment (N addition and weed control). Such losses can be broken down in reductions of up to 6.9% in rows per cob, 48% in grains per row, and 18.7% in grain weight. Failing to efficiently control weed infestation causes not only direct losses due to resource competition (such as nutrients, water, space, and light), but also contributes to the asynchrony of the anthesis-silking interval and acts as a physical barrier to pollination. Consequently, these factors can result in substantial yield losses. Our findings emphasize the crucial role of weed control in maize grown in tropical environments, as inter-specific competition can diminish the effectiveness of various agricultural practices, including fertilization, irrigation, and soil tillage, ultimately greatly compromising crop yield.

Declaration of competing interest

None.

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