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RESEARCH

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Estimating the impact on maize production by the weed *Parthenium hysterophorus* in Pakistan

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Abstract

Parthenium hysterophorus L. (Asteraceae) is an aggressive annual herbaceous weed which causes severe yield losses on a global scale. However, the precise impact of this weed in several countries is not yet known. To assess the impact of *P. hysterophorus* on maize crop losses in Pakistan, a 2 year field experiment was carried out at the CABI Rawalpindi campus in 2019 and 2020. Yield was measured on maize plants planted along with different densities (0, 1, 2, 4, 8, and 16 plants per m^2) of *P. hysterophorus*. The trial was laid in a randomized complete block design with five replicates per density each year. The highest maize seed yield was obtained in weed-free plots (4256.5 ± 118 kg ha^{-1}), while maize yield at weed infestation levels of 1, 2, 4, 8 and 16 plants m^{-2} was reduced by 14, 22, 29, 38 and 46%, respectively, compared to weed free plots. In the light of these findings, to reduce yield losses to non-significant levels it is proposed to reduce *P. hysterophorus* densities below 2 plants per m^2 in maize fields.

Keywords Allelopathy, Competition, Yield loss, Weed, Maize

Introduction

Maize (*Zea mais* L.) is the third most important food crop after wheat (*Triticum aestivum* L.) and rice (*Oryza sativa* L.) across the globe. Likewise, in Pakistan, maize is among the predominant crop species planted (Safdar et al. 2015), its production occupying an area of approximately 1.32 million hectares, with an average yield of approximately 4787 kg per hectare in the Province of Punjab (Economic Survey of Pakistan 2018–19). Weeds in maize fields may cause considerable yield losses worldwide, however, variations in different fields may range between 35 and 83% (Usman et al. 2001).

Parthenium hysterophorus L., Asteraceae, is native to Central and South America, Mexico, and the Caribbean (Adkins and Shabbir 2014) and it has become invasive in much of the world, including Australia, Asia, Africa, and the Middle East (Adkins et al. 2018). In Pakistan, *P. hysterophorus* was introduced in the 1980's, first in the Gujrat district of the Punjab province (Razaq et al. 1994), and later in several other districts of the Punjab and Khyber Pakhtunkhwa (Shabbir et al. 2012). Accordingly, *P. hysterophorus* is considered as a high impact invasive weed in Pakistan (Qureshi et al. 2014).

Due to its prolific viable seed production (Nguyen et al. 2017), as well as its rapid germination and growth rate, *P. hysterophorus* can rapidly invade crop fields (Al Ruheili et al. 2022). Accordingly, *P. hysterophorus* densities in various crop fields range from a few plants up to 370 plants m^{-2} (Tamado et al. 2002). Additionally, *P. hysterophorus* has been shown to produce allelopathic

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compounds, which can suppress the growth of neighbouring crops and pasture plants (Shi and Adkins 2020). Hence, *P. hysterophorus* invasion of crop fields can cause dramatic yield losses, such as in Australia, where *P. hysterophorus* invasion has been shown to have caused millions of dollars in crop yield losses (Shi et al. 2021). Similarly, it has been reported that this weed can cause yield losses of up to 40% in various crops, and a reduction of 90% in forage production in India (Gnanavel and Natarajan 2013; Tanveer et al. 2015). Moreover, seed yield reduction between 16 and 86% in common bean (*Phaseolus vulgare* L.) was observed in plots infested with up to 21 parthenium plants (Woldesenbet 2012), while sorghum grain yield was decreased from 40 to 95% in uncontrolled plots (Tamado et al. 2002). These results demonstrate that the effect of *P. hysterophorus* on crops is highly context dependent, and vary according to the intensity of infestation.

More specifically, yield losses likely depend on weed-crop competition dynamics, and for estimating economic impacts, the minimal density of weed plants in crop fields should be estimated independently for each system (Tanveer et al. 2015; Mahajan and Chauhan 2022) For instance, Safdar et al. (2015) calculated that the economic threshold of *P. hysterophorus* in Pakistan should be between 1.0 and 1.2 plants m^2, based model predictions of yield losses. Therefore, to address the potential economic threshold of *P. hysterophorus* in Pakistani maize fields, which are implementing novel cultivars that can sustain narrower spaces between rows, we performed a competition experiment with the maize cultivar CORTEVA 30K08. We predicted that higher densities would incur higher levels of yield loss overall, but that a minimal threshold density could be estimated for sustaining a positive economic yield.

Materials and methods

Field experiments were conducted during 2019 and 2020 at the CABI Regional Bioscience Centre in Rawalpindi to evaluate the impact of *P. hysterophorus* on maize yield at different weed densities (0, 1, 2, 4, 8, and 16 plants per m^2). The trial was performed using a randomized complete block design, with five replicates of 4 m^2 for each treatment. The soil was a sandy loam with a pH of 7.4, EC of 0.316 dS m^{-1}, available P of 11.4 mg kg^{-1}, available K of 102 mg kg^{-1}, and 1.24% organic matter.

Maize kernels (*Zea mays*, 'CORTEVA 30K08') were hand-sown on the 9th and 3rd of August, 2019 and 2020, respectively, in 2 × 2 m plots at a depth of 5 cm. Each plot comprised three rows of maize plants with between and within-row spacing was narrower than typical maize varieties at 60 and 20 cm, respectively, resulting in a plant density of 65,000–70,000 plants per hectare. Ploughing and disking were performed for seedbed preparation. Nitrogen fertilizer as urea (46% N) was applied at the rate of 250 kg N ha^{-1} so that half of the fertilizer was applied at sowing and the remaining was top-dressed at the knee height stage. Phosphorous and potassium at the rate of 120 kg P ha^{-1} and 125 kg K ha^{-1} were applied before sowing.

Plots were irrigated at 10–11 irrigation frequencies according to the ordinary local practice, following the production plan of maize crop developed by Ayub Agriculture Research Institute, Faisalabad, Pakistan. All plots were kept free from pests and diseases during the growing seasons. Seeds of *P. hysterophorus* were collected in May–June, 2019 during the growing season from a local population at the research farm of CABI, Rawalpindi, and were kept in sealed bags at 5 °C until germination prior to the experimental setup. Each weed density was achieved by transplanting seedlings roughly 2 weeks after maize germination at the four-leaf stage at the treatment rate of 1, 2, 4, 8, and 16 plants per m^2. Weed density for each treatment were maintained via weeding by hand once a week. No chemical herbicides were applied in this experiment. To determine maize yield and yield components, a 1 m^2 section from the middle two rows of each plot was harvested in November of 2019 and 2020.

To estimate the effect of *P. hysterophorus* weed density on the different response variables measured, we performed quadratic (yield losses, yield (Kg of grain per ha), number of cobs per plant, weight of 1000 grains), and linear (number of grains per cob number of cobs per plot, number of grains per row) models, respectively. Since there were no significant ($P > 0.05$) interactions between the 2019 and 2020 growing seasons for the effect of weed density on corn yield and yield components, the data from both years were combined.

Results

Maize yield and yield components

Overall, all metrics of maize yield declined with increasing weed competition (Figs. 1, 2, Table 1, 2). The highest maize yield was obtained in weed-free plots (Fig. 1A, 4256.5 ± 118 kg ha^{-1}) while, yield of maize plants added with weed infestation of 1, 2, 4, 8, and 16 plants m^2 was reduced by 14, 22, 29, 38, and 46%, respectively, compared to weed-free plots (Fig. 2). Accordingly, crop yield loss at maximum weed density reached 45.13% compared to weed free maize plants (Fig. 2). The change in some yield parameters with increasing weed competition follows a steady linear decline (see Fig. 1B, D, E, Table 1), while for others, a quadratic model was clearly a better fit (see Figs. 1A, C, F, and 2, Table 1). These results indicate that the effect of weed competition

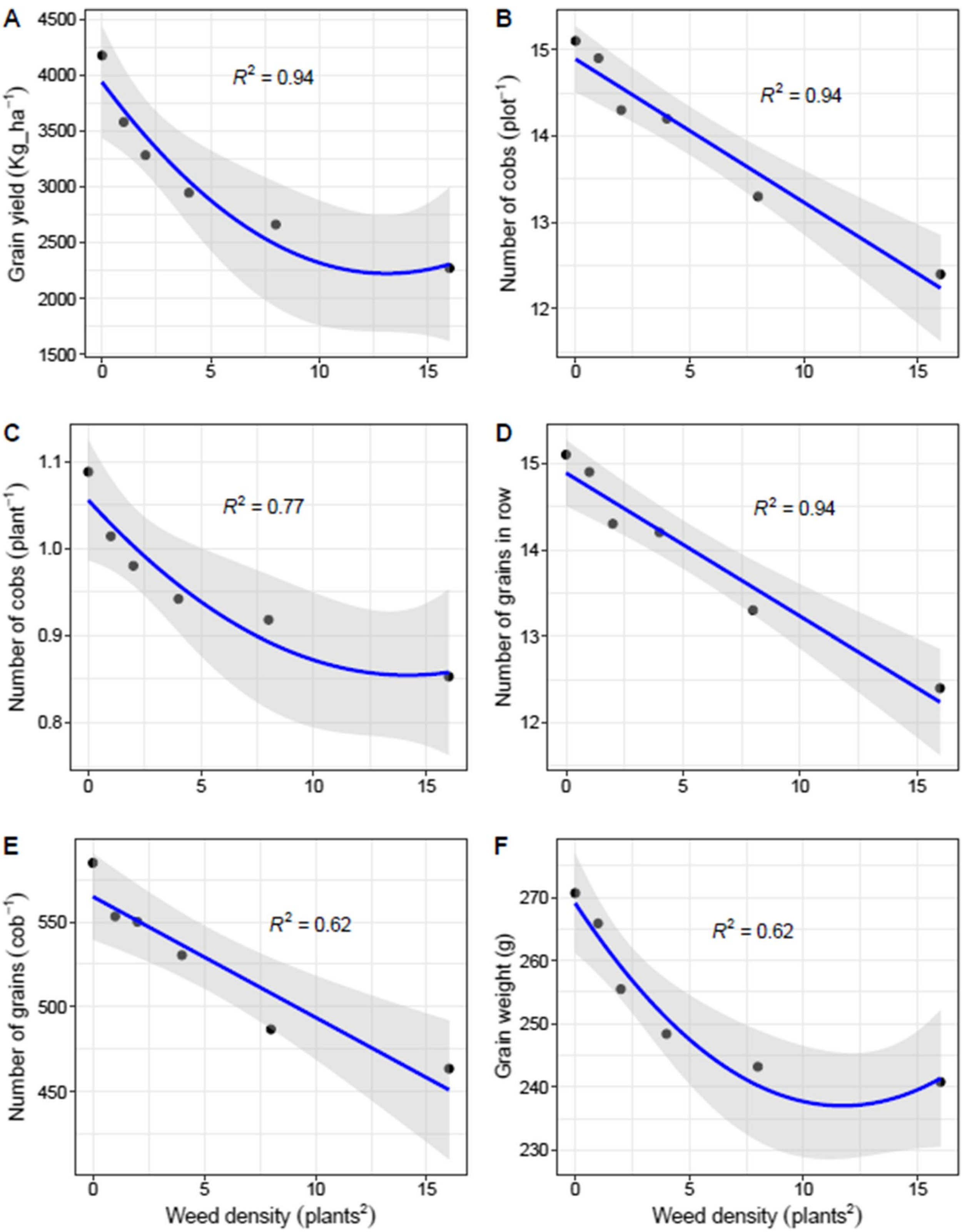

Fig. 1 Effect of *Parthenium hysterophorus* density on maize ('CORTEVA 30K08') yield and yield components (**A**: grain yield, **B**: number of cobs per plot, **C**: number of cobs per plant, **D**: number of grains per row; **E**: number of grains per plot; **F**: 1000 grain weight). Data were pooled across both years. Blue lines represent the best fit a linear or quadratic models, and grey shadings represent 95% confidence intervals around the fit

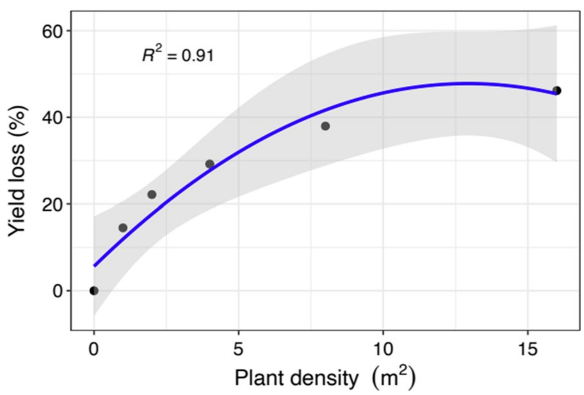

Fig. 2 Yield loss of maize (*Zea mays* 'CORTEVA 30K08') as affected by various densities of *Parthenium hysterophorus*. Symbols show means from ten replications, five in 2019 and five in 2020 (Data were pooled across both years). The blue line represents the best fit a quadratic model, and grey shading represents 95% confidence intervals around the fit

on maize yield initially increased rapidly at low densities of the weed but were already saturated at densities of 8 plants per m^2.

Discussion

The reduction of maize yield caused by increased density of *P. hysterophorus* found in the present study highlights the high competitive ability of this weed against maize, even at smaller within and between row spacing. It has been reported that maize yield decreased in a linear fashion from 20 to 46% in plots infested with between 5 and 20 *P. hysterophorus* m^{-2} (Safdar et al. 2015), but in the present study, a reduction of 46% in maize yield was observed already at a weed density of 16 plant m^{-2}. In addition, a linear decrease in maize grain yield was previously reported (Safdar et al. 2015), however, in the current study there we observed nonlinear responses, such as with the rate of yield loss, already decelerating after 4 plants m^{-2}, which might suggest intraspecific competition of the weed itself (Blackshaw et al. 2002). A similar trend was observed on oilseed rape (*Brassica napus*) plants, in which yield declined with a nonlinear fashion in response to increasing densities of wild mustard (*Sinapis arvensis*), also likely indicating intraspecific competition among wild mustard plants at the highest densities (Naderi and Ghadiri 2011). However, independently of the shape of the negative response curve, several crop plants have also been shown to suffer from the competition with weeds. For example, a reduction of up to 40% in grain yield has been shown for rice (*Oryza sativa* L.), wheat (*Triticum aestivum* L.), maize, teff (*Eragrostis tef* Zucc. Trotter), arhar (*Cajanus cajan* L.), blackgram (*Phaseolus mungo* L.), or sorghum (*Sorghum bicolour* L.) (Khosla and Sobti 1979 and 1981; Tamado et al. 2002; Shabbir 2006).

Here, although weed density caused a reduction in all yield components, the impact on number of cobs per plot and number of grains per cob was more severe than 1000-grain weight (see linear versus non-linear declines across parameters). Thus, the yield reduction in maize resulting from the interference of *P. hysterophorus* could be primarily due to a lower number of cobs per plot and number of grains per cob, than to grain weight. The reduced number of grains per cob as a result of increased weed density suggests that competition may be at its greatest during ear development and fertilization stage (Safdar et al. 2015). Other researchers also found that the number of grains in maize declined drastically as the densities of *Xanthium strumarium* (Karimmojeni et al. 2010) and *P. hysterophorus* (Safdar et al. 2015) increased. Hence, monitoring and reducing *P. hysterophorus* density before ear development stage should be considered by producers (Table 2).

The severe yield reduction observed in our study might be primarily due to greater resource competition at higher *P. hysterophorus* densities and/or longer competition periods. It has been shown that *P. hysterophorus* could uptake a higher amount of nutrients from the rhizosphere at higher densities

Table 1 Yield parameters measured on maize (*Zea mays* 'CORTEVA 30K08') plants levels of competition intensity with *Parthenium hysterophorus* (0, 1, 2, 4, 8, or 16 plants m^{-2})

Weed density (Plants m^{-2})	Grain yield (Kg ha^{-1})	Cob $plot^{-1}$ (No. $plot^{-1}$)	Cob $plant^{-1}$ (No. $plant^{-1}$)	Grain row^{-1} (No.row^{-1})	Grains cob^{-1} (No.cob^{-1})	1000grain weight (g)
0	4256 ± 118a	26.9 ± 1.1a	1.09 ± 0.01a	15.1 ± 0.4a	584.6 ± 16a	270.7 ± 6a
1	3580 ± 46b	24.8 ± 0.8ab	1.01 ± 0.03ab	14.9 ± 0.6a	553.2 ± 18ab	265.5 ± 7a
2	3283 ± 76bc	23.6 ± 0.7b	0.98 ± 0.03ab	14.3 ± 0.8ab	550.0 ± 20ab	255.5 ± 8ab
4	2947 ± 124cd	22.9 ± 0.8bc	0.94 ± 0.04bc	14.2 ± 0.4ab	530.4 ± 13b	248.4 ± 5b
8	2663 ± 116de	22.4 ± 0.9bc	0.92 ± 0.01bc	13.3 ± 0.4bc	486.9 ± 15c	243.2 ± 4b
16	2273 ± 93e	20.5 ± 0.7c	0.85 ± 0.02c	12.4 ± 0.4c	463.8 ± 16c	240.8 ± 6b

Data were pooled across both years

Table 2 ANOVA table showing results of linear and quadratic regression models for measuring the effect of *Parthenium hysterophorus* density on maize (*Zea mays* 'CORTEVA 30K08') yield loss (%), yield (Kg of grains per ha), number of cobs per plot, number of cobs per plant, number of grains per cob, and weight of 1000 grains per treatment

Response variable	Figure	Variable	Estimate	SE	t-value	Pr(>|t|)	
Yield	Figure 1A	Intercept	3936.78	156.66	25.13	< 0.001	***
		Weed_density	− 261.16	62.16	− 4.2	0.025	*
		Weed_density^2	9.96	3.72	2.68	0.075	
Cobs per plot	Figure 1B	Intercept	14.89	0.14	108.77	< 0.001	***
		Weed_density	− 0.17	0.02	− 9.12	0.001	***
Cobs per plant	Figure 1C	Intercept	1.06	0.02	48.7	< 0.001	***
		Weed_density	− 0.03	0.01	− 3.3	0.046	*
		Weed_density^2	0	0	1.94	0.147	
Grains in row	Figure 1D	Intercept	14.89	0.14	108.77	< 0.001	***
		Weed_density	− 0.17	0.02	− 9.12	0.001	***
Grains per cob	Figure 1E	Intercept	564.77	9.09	62.1	< 0.001	***
		Weed_density	− 7.09	1.21	− 5.88	0.004	**
Grain weight	Figure 1F	Intercept	269.1	2.47	109.11	< 0.001	***
		Weed_density	− 5.48	0.98	− 5.6	0.011	*
		Weed_density^2	0.23	0.06	4	0.028	*
Yield loss	Figure 2	Intercept	5.65	3.62	1.56	0.216	
		Weed_density	6.52	1.44	4.54	0.020	*
		Weed_density^2	− 0.25	0.09	− 2.94	0.061	

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

(Asif et al. 2017; Safdar et al. 2015), allowing the weed to grow faster thus impacting the crop yield. Additionally, because of producing and releasing secondary metabolites or allelochemicals in the root zone, *P. hysterophorus* might inhibit the growth of neighbouring species (Belz et al. 2007; Singh et al. 2003; Shi and Adkins 2020). The weed is also known to alter soil physical and microbial properties so that it favours its growth while limiting the moisture and nutrients supply to its co-existing species (Timsina et al. 2011), and it eventually decreases crop yield.

In crop–weed interactions, weed and crop densities play a crucial role in competition (Mahajan and Chauhan 2022). However, in the present study, maize density remained constant, suggesting that the observed effects were predominantly driven by changes in the weed densities, as was shown by Tanveer et al (2015). That said, weed competitiveness might be different across different crop cultivars, growing seasons, moisture regimes, and weed populations (Carlson and Hill 1985). The relative time of emergence of weeds and crops may also affect the competitive ability of the weed (Mahajan and Chauhan 2022). Thus, exploring the potential of cultural weed management strategies like sowing time and rate, evaluating competitive cultivars, and row spacing under various environmental conditions and variables are of importance for future studies.

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RN, PW and SR, conceptualization, data analysis and writing; KA and AR, conceptualization, experimentation, data collection. All authors read and approved the final manuscript.

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Availability of data and materials
The datasets during and/or analysed during the current study available from the corresponding author on reasonable request.

Declarations

Ethics approval and consent to participate
Not applicable.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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