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DTPA-extractable zinc threshold for wheat grain yield response to zinc fertilization in Mollisols

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Abstract

Determining soil Zn thresholds for wheat (*Triticum aestivum* L.) is still challenging because soil Zn tests have been poorly calibrated. Therefore, this work aimed to determine, under field conditions, the diethylenetriaminepentaacetic acid (DTPA)–Zn critical threshold for wheat grain yield (GY) response to Zn fertilization in noncalcareous Mollisols. We conducted 14 Zn-fertilization field trials in Typic Argiudolls from the Argentinean Pampas. Zinc fertilization increased GY in 6 out of 14 trials. Wheat GY response to Zn fertilization ranged from 300 to 949 kg ha^{-1}. Our DTPA–Zn threshold is the first one determined by field trials for wheat grown in Mollisols (1.03 mg kg^{-1}, with a 95% confidence interval from 0.87 to 1.23 mg kg^{-1}). This threshold was greater than those previously reported for other soil types. Future studies should compare different Zn-fertilization strategies for wheat on Mollisols by combining different fertilizer rates, sources, timings, and placements.

1 | INTRODUCTION

Wheat (*Triticum aestivum* L.) grain yield (GY) is often limited by soil Zn deficiencies resulting from pedogenetic and/or anthropogenic causes (Cakmak et al., 2017). Mollisols cover 916 million ha worldwide and are recognized as inherently productive and fertile soils (Liu et al., 2012). Because pristine Mollisols have been shown to present high Zn fertility (Sainz Rozas et al., 2015), Zn deficiencies in these soils are associated with the depletion of this micronutrient resulting from Zn export with grains without an adequate Zn replenishment by fertilization. To avoid Zn deficiencies in wheat caused by insufficient Zn fertilization, as well as the negative economic and environmental impact of overfertilization, it is necessary to develop accurate extraction methods to estimate soil Zn availability.

Soil test correlation is the process of determining whether there is a relationship between GY and the concentration of nutrients extracted by a particular soil test (Dahnke & Olson, 1990). Pot correlation tests are useful and inexpensive approaches to determine the suitability of an extraction method for a given soil type (Dahnke & Olson, 1990). Previous pot studies showed a moderate correlation between relative yield (RY) and the Zn extracted by the diethylenetriaminepentaacetic acid (DTPA) method (Lindsay & Norvell, 1978) in wheat plants grown in calcareous Mollisols (Sakal et al., 1979; Srivastava et al., 2008). However, a critical threshold of soil nutrient availability to predict GY response must be determined by field trials (Dahnke & Olson, 1990). The DTPA–Zn has adequately discriminated Zn-responsive sites when corn (*Zea mays* L.) is grown in Mollisols (Barbieri et al.,

Abbreviations: DTPA, diethylenetriaminepentaacetic acid; GY, grain yield; RY, relative yield; SOM, soil organic matter.

2017; Martínez Cuesta et al., 2020). Nevertheless, a DTPA–Zn critical threshold must be defined for each specific soil and crop, as the thresholds vary depending on the soil nutrient supplying capacity and the crop use efficiency (Tagore et al., 2017).

As far as we know, the acid-neutral pH range of noncalcareous Mollisols has not been explored in terms of the correlation between wheat GY response to Zn fertilization and DTPA–Zn. Also, there are no field correlations of this method for wheat grown in Mollisols. Therefore, the objective of this work was to determine, under field conditions, the DTPA–Zn critical threshold for wheat GY response to Zn fertilization in noncalcareous Mollisols.

Core Ideas

- Wheat grain yield response to Zn fertilization ranged from 300 to 949 kg ha^{-1} on Mollisols from Argentina.
- Diethylenetriaminepentaacetic acid–Zn adequately correlated (r = .77) with the wheat grain yield response to Zn fertilization.
- The determined DTPA–Zn critical threshold was 1.03 mg kg^{-1}.

2 | MATERIALS AND METHODS

From 2010 to 2019, we conducted 14 wheat Zn-fertilization field trials on noncalcareous, Typic Argiudolls (U.S. Soil Taxonomy) in the Argentinean Pampas (Figure 1). This soil type is characterized by well-developed profiles, with surface horizons rich in soil organic matter (SOM; mollic epipedon) without significant content of carbonates, and with an argillic subsurface horizon (Bt) (Rubio et al., 2019). All trials were performed under no-tillage and rainfed conditions. The experimental design at each trial was a randomized complete block arrangement with three replications (plot size: 10 m long by 4 m wide). Treatments were (a) Control, without Zn fertilization, and (b) Zn-fertilized. The Zn rates and application methods varied among trials and followed the recommendations from the manufacturers (Table 1). The varied Zn fertilization methods represent a strength rather than a weakness of our study because a Zn-availability index must be robust enough to function under the various application strategies commonly used by farmers. Sufficient N, P, and S fertilization were ensured at all trials. Further information on the location, wheat variety, and sowing date at each trial is described in Supplemental Table S1.

Before wheat sowing, composite soil samples (15 cores, 0-to-20-cm depth) were taken from each block at each trial. Soil samples were dried at 35–40 ˚C and ground to pass through a 2-mm sieve. Soil pH (1:2.5 soil/water ratio), SOM (Schulte & Hopkins, 1996), and soil DTPA-extractable Zn (Lindsay & Norvell, 1978) were determined. At the Z_{92} stage (Zadoks et al., 1974), wheat GY was determined by hand-harvesting the central four crop rows (4 m long) from each plot, and it was expressed at a 140 g kg^{-1} moisture content. The GY response to Zn fertilizer was analyzed in each trial using ANOVA at

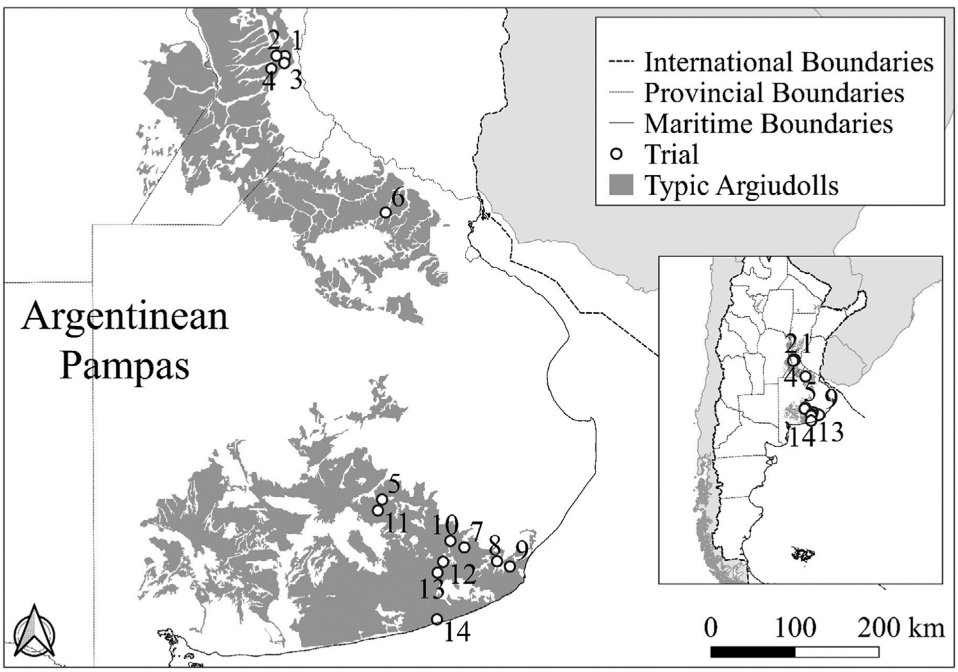

FIGURE 1 Typic Argiudolls soil map of the Argentinean Pampas at a regional scale of 1:500,000, indicating the location of 14 Zn-fertilization trials on wheat

TABLE 1 Soil properties, wheat grain yield, and Zn application methods for 14 Zn-fertilization field trials

Trial	DTPA–Zn[a]	pH	SOM[b]	GY Control[c]	GY + Zn[d]	*p* value[e]	Zn application method
	mg kg^{-1}		g kg^{-1}	kg ha^{-1}			
1	0.90	5.9	22	5,866	6,815	.04	1.5 kg Zn ha^{-1} as $ZnSO_4$ surface banded at Z_{21}
2	0.97	5.7	21	2,446	2,746	.03	1.5 kg Zn ha^{-1} as $ZnSO_4$ surface banded at Z_{21}
3	0.75	5.3	18	4,549	4,806	.14	1.5 kg Zn ha^{-1} as $ZnSO_4$ surface banded at Z_{21}
4	1.02	5.9	25	5,490	6,130	.01	28 g Zn kg^{-1} seed coating as Zn-EDTA
5	2.40	5.6	42	6,583	6,258	.22	32 g Zn kg^{-1} seed coating as Zn-EDTA
6	0.80	5.9	28	5,510	5,893	.04	0.9 kg Zn ha^{-1} soil banded applied at sowing
7	1.20	7.6	70	5,463	5,490	.46	0.9 kg Zn ha^{-1} soil banded applied at sowing
8	0.90	5.8	54	5,784	5,916	.76	1.1 kg Zn ha^{-1} as ZnO foliar applied at Z_{31}
9	1.70	6.4	48	6,057	6,317	.54	1.1 kg Zn ha^{-1} as ZnO foliar applied at Z_{31}
10	1.20	5.7	55	5,398	5,733	.23	1.1 kg Zn ha^{-1} as ZnO foliar applied at Z_{31}
11	0.60	5.9	44	3,970	4,415	.02	1.1 kg Zn ha^{-1} as ZnO foliar applied at Z_{31}
12	1.33	5.8	49	8,307	8,453	.99	1.1 kg Zn ha^{-1} as ZnO foliar applied at Z_{31}
13	2.10	6.6	71	5,171	5,070	.67	1.1 kg Zn ha^{-1} as ZnO foliar applied at Z_{31}
14	0.57	6.3	41	6,531	7,363	.02	1.1 kg Zn ha^{-1} as ZnO foliar applied at Z_{31}
Avg.	1.17	6.03	42	5,509	5,815		
SD	0.55	0.56	17	1,340	1,358		
Median	1.00	5.9	43	5,500	5,904		
Min.	0.57	5.3	18	2,446	2,746		
Max.	2.40	7.6	71	8,307	8,453		

[a]Soil diethylenetriaminepentaacetic acid (DTPA) extractable.
[b]Soil organic matter.
[c]Grain yield on Zn-unfertilized (control).
[d]Grain yield on Zn-fertilized.
[e]ANOVA *p* value for the grain yield comparison between control and Zn-fertilized.

$p < .05$. The RY was calculated by dividing the GY of the Control treatment at each trial by the GY of the Zn-fertilized treatment, multiplied by 100. The arcsine–logarithm calibration curve (Correndo et al., 2017) was used to describe the relationship between soil Zn availability (DTPA–Zn) and RY.

3 | RESULTS AND DISCUSSION

The experimental sites presented soil pH ranging from acidic to slightly alkaline (5.3–7.6), and a wide range of SOM (18–71 g kg^{-1}) and soil DTPA–Zn (0.57–2.40 mg kg^{-1}) (Table 1). All these values were within the ranges previously reported for agricultural soils from the studied region (Sainz Rozas et al., 2015). Wheat GY ranged from 2,446 to 8,307 kg ha^{-1} in the Control treatment, and from 2,746 to 8,453 kg ha^{-1} in the Zn-fertilized treatment (Table 1). Grain yield response to Zn fertilization was observed in 6 of 14 trials ($p < .05$). In responsive sites, soil DTPA–Zn values ranged from 0.57 to 1.02 mg kg^{-1}, and GY response to Zn fertilization ranged from 300 to 949 kg ha^{-1}.

The fitted arcsine–logarithm calibration curve {DTPA–Zn $= e^{[-4.5+3.37\times\arcsin\sqrt{(RY/100)}]}$}, which describes the relationship between wheat RY and soil DTPA–Zn, presented

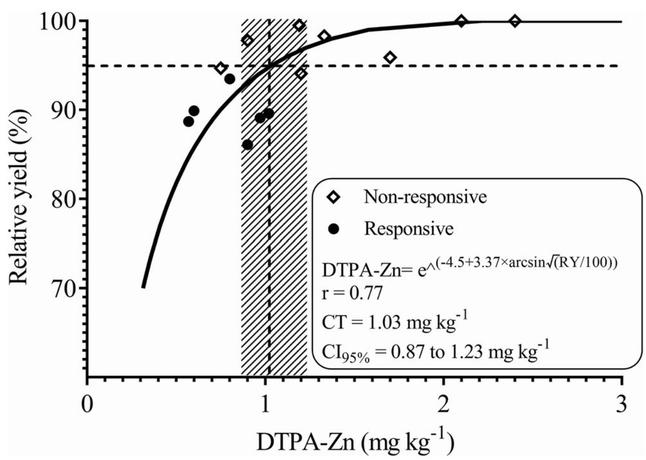

FIGURE 2 Relationship between wheat relative yield (RY) and soil diethylenetriaminepentaacetic acid (DTPA)–Zn content (0–20 cm) across 14 trials using the modified arcsine–logarithm calibration curve. CT, critical soil zinc test threshold estimated at a 95% RY; $CI_{95\%}$, 95% confidence interval for CT

a correlation coefficient of 0.77 (Figure 2). Using a sufficiency level approach, the soil DTPA–Zn critical threshold necessary to achieve a fixed 95% RY goal was 1.03 mg kg^{-1}, with a 95% confidence interval from 0.87 to 1.23 mg kg^{-1} (Figure 2). The fitted curve can also be used to determine a variable economic threshold, following the procedure described by Martínez Cuesta et al. (2020).

A summary of published DTPA–Zn thresholds for wheat from different pot and field studies is presented in Supplemental Table S2. The DTPA–Zn critical threshold in the present study (1.03 mg kg^{-1}) was greater than those reported for calcareous Mollisols in pot studies (0.53-0.57 mg kg^{-1}; Sakal et al., 1979; Srivastava et al., 2008). Overall, within the same soil type, critical thresholds seemed to be lower when determined in pot studies than those determined in the field (Supplemental Table S2). Some possible reasons explaining this trend are: (a) GY of plants growing in pots are mainly limited by the volume of soil available for root growth rather than by soil Zn availability (Poorter et al., 2012); (b) soil in pots generally suffer some disturbance; and (c) soil temperature in pots is higher than soil temperature under field conditions (especially for winter crops; Passioura, 2006), which may increase Zn diffusion, and thus, Zn availability for plants (Schwartz et al., 1987; Ma & Uren, 1997).

Previous studies showing field correlations for wheat reported lower DTPA–Zn thresholds (0.59 and 0.75 mg kg^{-1}, respectively; Bansal et al., 1990; Tagore et al., 2017) than the one determined in our study (Supplemental Table S2). The soil type may explain these differences because these other studies have been carried out in Inceptisols and Vertisols with higher carbonate content and pH than those in our study (Supplemental Table S2). In that sense, sorption on the surface of $CaCO_3$, coprecipitation with carbonates, and formation of calcium zincate all reduce the amount of soil Zn extracted by DTPA in calcareous soils (Baruah, 2018). High carbonate content also increases soil pH, which is a driving factor of Zn availability, because the solubility of Zn minerals and the Zn desorption from clays and oxides decreases with increasing soil alkalinity (Catlett et al., 2002; Fernández et al., 2015).

In soils from the Pampas region, Barbieri et al. (2017) and Martínez Cuesta et al. (2020) reported DTPA–Zn critical thresholds for corn (0.99 and 1.02 mg kg^{-1}, respectively) similar to the one determined for wheat in the present study. Although corn has a greater potential yield than wheat, and thus a greater absolute demand for Zn per unit area, both crops have similar aboveground Zn requirement for grain production (~42–55 g Zn Mg^{-1}) (Nayyar et al., 2001; Bender et al., 2013; Ciampitti & Vyn et al., 2013; Liu et al., 2019). Also, wheat GY response to Zn fertilization and RY were not correlated with the maximum yield at each site ($p = .54$ and $p = .62$, respectively). This behavior has already been reported for Zn in corn (Barbieri et al., 2017; Martínez Cuesta et al., 2020) and other nutrients with low soil mobility (Dodd & Mallarino, 2005) that reach the root surface by diffusion and root interception (Bray, 1954). These observations suggest that the GY response to Zn fertilization is more related to the capacity of soils to provide available Zn to the roots than to the absolute crop demand for Zn. In other words, a higher absolute Zn demand by the crop (resulting from a higher potential yield) is compensated for by larger root growth and soil exploration, which enhances the access of the plant to soil Zn. Consequently, the critical threshold did not differ between wheat and corn.

To sum up, this study showed that below 1.03 mg kg^{-1} DTPA–Zn, wheat GY response to Zn fertilization is expected in noncalcareous Mollisols. This threshold was greater than those previously reported for calcareous soils. The new threshold is expected to assist in closing the yield gap for wheat in noncalcareous Mollisols through a more efficient Zn management; it will avoid Zn deficiencies that would be underestimated if the thresholds determined for other soil types were used. Future studies should compare different Zn-fertilization strategies for wheat on Mollisols by combining different fertilizer rates, sources, timings, and placements.

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AUTHOR CONTRIBUTIONS

Nicolás Martínez Cuesta, Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Writing-original draft, Writing-review & editing; Walter D. Carciochi, Investigation, Methodology, Writing-original draft; Fernando Salvagiotti, Funding acquisition, Investigation, Writing-review & editing; Hernán Rene Sainz Rozas, Funding acquisition, Project administration, Supervision; Pablo Andres Barbieri, Data curation, Formal analysis, Supervision.

CONFLICT OF INTEREST

The authors declare no conflicts of interest.

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