Plant Soil (2012) 361:43–55
DOI 10.1007/s11104-012-1434-x

REGULAR ARTICLE

Value of soil zinc balances in predicting fertilizer zinc requirement for cotton-wheat cropping system in irrigated Aridisols

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Received: 29 December 2011 / Accepted: 17 August 2012 / Published online: 6 September 2012

Abstract
Aims The cotton (*Gossypium hirsutum* L.)-wheat (*Triticum aestivum* L.) cropping system practised in >3 million ha of irrigated Aridisols in Pakistan is pivotal to its national economy and food security. Thus, the prevalent stagnation in its productivity is a matter of serious concern. Widespread deficiency of zinc (Zn) in these low organic matter alluvial calcareous soils is amongst the suspected constraints. Therefore, studying the impact of improved nutrient management strategies and crop residue recycling on crop productivity and soil Zn balances was thought imperative.
Methods A 5-year permanent layout field experiment was conducted on two predominant soil series of the cotton-wheat belt [i.e., Awagat (coarse loamy mixed, hyperthermic Fluventic Camborthid) and Shahpur (fine silty mixed, hyperthermic Fluventic Camborthid)] to compare the impact of (1) Farmers' fertilizer use (FFU); (2) Recommended fertilizer use (RFU); and (3) Integrated nutrient management (INM) on crop productivity and apparent soil Zn balances. The nutrient management strategies were compared with and without cotton-wheat residue recycling, in flat-bed sown and raised-bed sown cotton systems.
Results Under the FFU treatment, Zn deficiency occurred both in wheat and cotton. Overall lowest mean yields (Mg ha^{-1}), obtained with FFU, were: seed cotton—Awagat, 2.19; Shahpur, 2.45; wheat grain—Awagat, 3.03; Shahpur, 3.94. Yield increases with RFU were: cotton, 24 % in Awagat and 18 % in Shahpur soil; wheat, 37 % in Awagat and 24 % in Shahpur soil ($P \leq 0.05$). With INM, crop yields were slightly higher than with RFU. Also, cotton yields were ~10 % greater on raised beds than on flat beds. Crop residue also increased yield of both crops, up to 10 %. Zinc uptake patterns of both crops were closely related to their yields. Fertilizer Zn use efficiency by the cotton-wheat system, in both soils, was quite low, i.e., 1.78–2.36 % of the annually applied 5 kg Zn ha^{-1}. Thus, ~98 % of the applied Zn was retained (fixed) in the soils. Though Zn input from organic sources (i.e., crop residue and farm yard manure) was inadequate to meet crop requirements, Zn use efficiency from organic sources was much greater, i.e., 13–24 %. As Zn uptakes by the cropping system were quite low (i.e., 62–123 g Zn ha^{-1} by cotton; 74–170 g Zn ha^{-1} by wheat) compared with Zn inputs (i.e., 1.12–1.79 kg Zn ha^{-1} year^{-1}), all nutrient management treatments, including FFU, resulted in positive apparent Zn balances in both soils.

Responsible Editor: Ismail Cakmak.

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Conclusions Thus, unlike nutrient balances for macronutrients, apparent Zn balances have little significance in predicting fertilizer Zn need of the cropping system. Despite positive soil Zn balances, even without using fertilizer Zn, prevalence of Zn deficiency in cotton and wheat crops may be attributed to high Zn fixation in calcareous soils rather than low total Zn content in the soils. In this scenario, soil testing and plant analysis remain the reliable approaches for diagnosing Zn deficiency problem.

Keywords Apparent soil Zn balances · Cotton-wheat cropping system · Crop residue · Fertilizer Zn use efficiency · Irrigated Aridisols · Nutrient management · Zinc deficiency · Zinc uptake

Introduction

Sustained productivity of the irrigated cotton (*Gossypium hirsutum*, L.)-wheat (*Triticum aestivum* L.) system in >3.0 million ha of Aridisols in Pakistan is pivotal to the national food security and economic wellbeing. The Green Revolution of 1960s, i.e., adoption of high-yielding cereal crop varieties—with irrigation water and fertilizer use, resulted in increased crop productivity and farmer-income. However, as a consequence of enhanced nutrient mining, with minimal organic manure use and crop residue recycling, these intensively cultivated, low soil organic matter (SOM, 0.5–0.9 %) alluvial soils now suffer from deficiencies of multiple nutrients, including zinc (Zn) (Rafique et al. 2002). Fertilizer use in the cropping system is predominantly restricted to nitrogen (N) for cotton and N and phosphorus (P) for wheat; use of potassium (K) and micronutrients is rare (Rashid 2005). Also, N and P use rates are low and N:P use ratio is too wide, 9.2:1 (Government of Pakistan 2010), to cater for crop nutrient requirements. Thus, despite a progressive rise in N and P fertilizer use over the past couple of decades, crop productivity per unit area has remained almost stagnant (Government of Pakistan 2010). As key constraints to optimum productivity in such soils are deficiency of nutrients, including Zn; negligible use of organic manures; lack of crop residue recycling; and imbalanced and inefficient fertilizer use (Saleem 1994; Prasad and Sinha 2000), more effective nutrient management strategies are needed for sustaining the productivity of the cotton-wheat cropping system.

Zinc deficiency in crops is a common nutrient disorder around the globe, including Pakistan (Rashid 2005; Alloway 2008; Rashid and Ryan 2008), which hampers crop productivity and impairs nutritional quality of the crop produce (Graham and Welch 1996; Hotz and Brown 2004). In Pakistan, the prevalence of Zn deficiency in the irrigated cotton-wheat system, practised on alkaline-calcareous alluvial soils—predominantly Aridisols—is well recognized (Rashid 2005; Rashid and Ryan 2008; Ahmed et al. 2010). Fertilizer Zn use is recommended for both crops (Rashid 2005); however, the impact of Zn removal by intensive cotton-wheat cropping and Zn addition by fertilization, irrigation water, and crop residue on Zn balance is inadequately understood. Therefore, we investigated the impact of various nutrient management strategies on apparent Zn balances in two predominant irrigated Aridisols and its value in predicating fertilizer Zn requirement of the cropping system.

Materials and methods

A five-year permanent layout field study was conducted at two sites in the major cotton-wheat belt of the Punjab province, Pakistan, i.e., at Chak 5-Faiz on on Awagat series and at Chah A. Rahim on Shahpur series. Both the soil series represent predominant soils on which the cotton-wheat rotation is practised. The details of this field experiment were described elsewhere (Rafique et al. 2012).

Field soils, nutrient management treatments, and crop management

Both the soil series, i.e., Awagat (coarse loamy mixed, hyperthermic Fluventic Camborthid) and Shahpur (fine silty mixed, hyperthermic Fluventic Camborthid), belong to the *US Soil Taxonomy* Soil Order Aridisol. Properties of the surface soils (0–15 cm), collected prior to applying any nutrient treatment, are presented in Table 1.

The field study had 24 experimental plots, arranged in a split-split-plot design, with two replications. Two sowing methods for cotton, i.e., flat-bed (with flood irrigation) and raised-beds (with furrow irrigation), were in main-plots; two crop residue recycling

Table 1 Properties of the field soils (0–15 cm) at start of the experiment

Property	Awagat series	Shahpur series
Texture	Loam	Silty clay loam
Electrical conductivity (1:1) (dS m^{-1})	0.45	0.54
Organic matter (%)	0.60	0.85
pH (1:1)	8.0	8.4
$CaCO_3$ equiv. (%)	2.2	3.7
AB-DTPA[a] extractable (mgkg^{-1})		
NO_3-N	3.4	5.5
P	2.2	3.5
K	150	204
Zn	0.48	0.72
HCl extractable B (mgkg^{-1})	0.28	0.40

[a] *AB-DTPA* Ammonium bicarbonate-diethylenetriamine penta acetic acid

regimes, i.e., none (cotton stalks and wheat straw were physically removed) and residue (cotton stalks after last picking and leftover wheat straw after combine harvesting) recycled in sub-plots; and the following nutrient management treatments in sub-sub-plots:

(1) FFU Farmers' fertilizer use practice, i.e., 110 kg N ha^{-1} for cotton; 80 kgN+26 kg P ha^{-1} for wheat;

(2) RFU Recommended fertilizer use, i.e., 170 kgN +26 kg P+5 kg Zn+1 kg B ha^{-1} for cotton; 140 kg N+44 kg P ha^{-1} for wheat; and

(3) INM Integrated nutrient management, i.e., same as RFU, except that 75 %N applied as fertilizer and 25 % as farmyard manure (FYM).

Fertilizer sources were: urea/diammonium phosphate (DAP) for N; DAP for P; zinc sulfate for Zn; and borax for B. Fertilizers were applied by broadcasting during final seedbed preparation, and FYM (4,700 kgha^{-1} for cotton and 3,889 kgha^{-1} for wheat) was applied and mixed at the time of field preparation. Mean nutrient concentrations in FYM were: N, 0.90± 0.1 %; P, 0.10±0.01 %; K, 0.5±0.04 %; Zn, 14± 1.2 mgkg^{-1}; and B, 4±0.31 mgkg^{-1}.

Wheat (cv. *Inqlab*-91) was planted in December of each year and harvested in April of the following year. Thereafter, cotton (cv. CIM-496) was planted in May, picked manually during October-November without defoliating and stalks were harvested. Both crops received standard management practices (seed bed preparation, seed rates, planting methods, irrigation, cultural practices, plant protection measures and harvesting) of the area; detail is given elsewhere (Rafique et al. 2012). Cotton seed, wheat grain and biomass yields were recorded.

Soil and plant Zn analyses and crop Zn uptakes

After harvesting each crop, surface soil (0–15 cm) was sampled from all experimental plots. Soil Zn status was measured by ammonium bicarbonate [AB-diethylenetriaminpenta acetic acid (DTPA)] extraction (Soltanpour 1985) and atomic absorption spectroscopy (Wright and Stuczynski 1996). Composite, youngest fully matured cotton leaves (excluding petioles) from the main stem at flower initiation (Plank 1979), top two leaves of wheat at head emergence (Jones et al. 1991), and mature cotton seed, lint, bur, leaf, and stalk as well as mature wheat grain and straw, were sampled from each plot. Representative plant samples were digested in a HNO_3-$HClO_4$ mixture (2:1) and the digests were analyzed for Zn by atomic absorption spectroscopy (Wright and Stuczynski 1996).

Zinc uptake by cotton was estimated by multiplying mean yields of seed, lint, bur, leaf, and stalk dry matter with mean Zn concentration in respective plant parts. Zinc uptake by wheat was estimated by multiplying mean yields of grain and straw dry matter with mean Zn concentration in respective plant parts.

Zinc input–output measurements and soil Zn balances

Apparent partial Zn balances (all components measured in kg elemental Zn ha^{-1}) for the cropping system were calculated as:

$$Zn_{ab} = Zn_{inp}\left(Zn_f, Zn_m, Zn_i, Zn_r, Zn_c\right) - Zn_{outp}\left(Zn_{up}\right)$$

where Zn_{ab} is apparent Zn balance; Zn_{inp} is Zn input through fertilizer (Zn_f), farmyard manure (Zn_m), irrigation water (Zn_i), rain water (Zn_r) and crop residue (Zn_c); Zn_{outp} is Zn output through Zn uptake by cotton seed, lint, bur, leaf and stalk and wheat grain and straw (Zn_{up}).

At the Awagat soil field site, total irrigation water used for five crop cycles was 3,750 mm for flat-bed cotton, 3,000 mm for raised-bed cotton, and 1,850 mm for wheat. At the Shahpur soil field site, total irrigation water used was 3,500 mm for flat bed cotton, 2,950 mm for raised bed cotton, and 1,750 mm for wheat. About 50 % of irrigation water was provided each by canal and tubewell sources. Mean Zn concentrations in irrigation waters were: Awagat soil field site—canal as well as tubewell, 0.02 mgL^{-1}; rain, 0.015 mgL^{-1}; Shahpur soil field site—canal, 0.03 mgL^{-1}; for tubewell, 0.05 mgL^{-1}; rain, 0.02 mgL^{-1}..

Statistical analysis

Split-split plot design with two factors factorial was used for analysis of variance (ANOVA) of the measured parameters for each year using MSTAT-C and treatment means were compared using Duncan's multiple range test (DMRT) at 5 % probability level.

Results

Nutrient management, crop residue recycling and crop productivity

Crop yields as affected by nutrient management and crop recycling treatments, over the five-year period, are reported elsewhere (Rafique et al. 2012). Yield of both crops increased with RFU as well as with INM in both soils ($P \leq 0.05$). Lowest yields of both crops were observed with FFU; overall mean yield of seed cotton with FFU was 2.15 $Mgha^{-1}$ during first year, 2.13 Mg ha^{-1} during fifth year. With RFU and INM, yields of both crops increased progressively over the study years. Maximum yield of both crops in both soils were obtained with INM; positive impact of this FYM-included treatment was more obvious in coarse-textured Awagat soil. Wheat grain yield also increased with improved nutrient managements across the years in both soils ($P \leq 0.05$); lowest grain and straw yields were obtained with FFU, and INM produced maximum yields. . Similar to cotton, cumulative positive impact of RFU and INM was also observed on wheat productivity, and magnitudes of increase in wheat grain yield were higher in coarse-textured Awagat soil than in Shahpur soil.

Crop residue recycling increased yields of both crops in both soils; however, appreciable increases were observed during last 3–4 years of the experiment ($P \leq 0.05$). Seed cotton yields were higher on raised beds compared with flat bed ($P \leq 05$). However, yields of wheat crop planted after demolishing the raised beds of cotton were similar to yields planted at the flat-bed plot sites.

Zinc status of diagnostic leaves

Zinc concentration in recently matured leaves of cotton and wheat increased with both the improved nutrient management treatments ($P \leq 0.05$; Fig. 1). Cotton leaf Zn concentration increased with RFU and INM treatments across years, and with crop residue recycling during final years of the experiment ($P \leq 0.05$). For example, in Awagat soil, mean cotton leaf Zn concentration with FFU was 18 $mgkg^{-1}$, and maximum mean Zn concentration (i.e., 26 $mgkg^{-1}$) was attained with INM. Similarly, in Shahpur soil, mean cotton leaf Zn concentration with FFU was 20 $mgkg^{-1}$; mean Zn concentration with INM was 25 $mgkg^{-1}$. Similar to cotton, maximum Zn concentrations in wheat were observed with INM. For example, in Awagat soil, mean wheat leaf Zn concentration with FFU was 16 $mgkg^{-1}$, which increased up to 22 $mgkg^{-1}$ with INM. Crop residue incorporation also increased leaf Zn concentration slightly, but consistently; average increase in both crops was 1–2 $mgkg^{-1}$.

Crop Zn uptake and fertilizer Zn use efficiency

Total Zn uptake by cotton increased with RFU and INM across the years in both soils, and with crop residue recycling during the final year of the study only ($P \leq 0.05$; Table 4). Non-significant interaction effects (i.e., effect of cotton sowing method × crop residue recycling × nutrient treatment) on Zn uptake revealed that over the 5-year period all nutrient treatments resulted in similar Zn uptake increases. The lowest crop Zn uptake was observed with FFU while maximum with INM. As with yields, the Zn uptake was considerably higher with INM than with RFU. Over the experimental years, crop Zn uptake with FFU remained almost the same or was slightly reduced in both soils. However, positive impact of RFU and INM on Zn uptake became more evident during the final year of the field study. In Awagat soil, mean Zn uptake

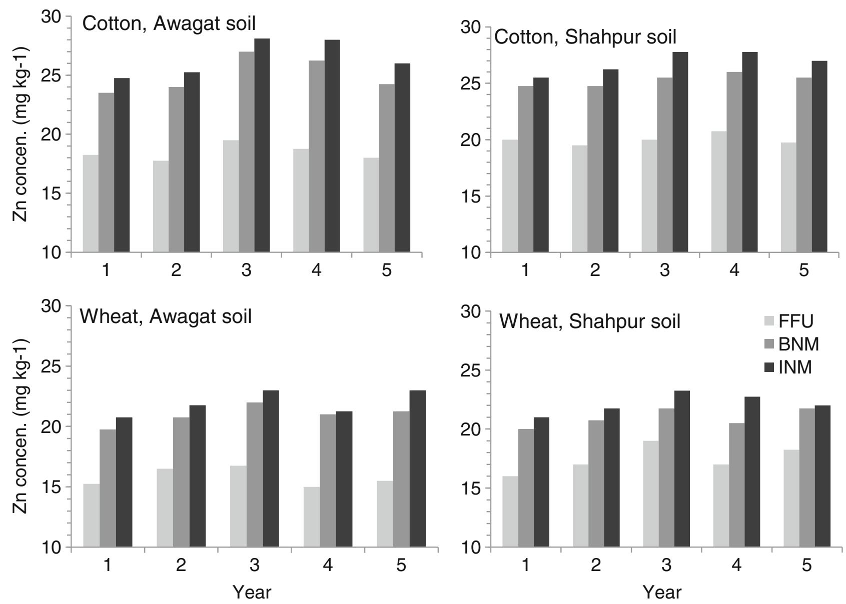

Fig. 1 Zinc concentration in recently matured leaves of cotton and wheat as affected by nutrient management treatments

Table 2 Five-year average Zn concentrations (mg kg^{-1}) in mature plant parts of cotton as affected by nutrient and crop residue management in two irrigated Aridisols. The values are means of two replicates

	Lint	Seeds	Bur	Leaves	Stalk	Lint	Seeds	Bur	Leaves	Stalk
	Awagat soil					Shahpur soil				
Flat bed										
Without residue										
FFU	5.9	16	4.4	14	5.8	6.4	18	5.3	15	6.8
RFU	6.8	21	6.3	19	8.8	7.1	22	6.7	19	9.2
INM	7.1	23	7.1	21	9.8	7.2	24	7.2	20	10.2
With residue										
FFU	6.2	17	4.8	15	6.2	6.6	19	5.5	16	7.6
RFU	7.1	22	6.6	20	9.2	7.3	24	6.9	20	9.8
INM	7.3	24	7.4	22	10.3	7.4	25	7.5	21	11.2
Raised beds										
Without residue										
FFU	6.1	16	4.7	15	6.2	6.5	19	5.4	15	7.4
RFU	7.0	22	6.5	20	9.4	7.2	23	6.8	20	9.8
INM	7.3	23	7.3	21	10.2	7.4	24	7.3	21	11.0
With residue										
FFU	6.3	18	5.0	15	6.9	6.7	19	5.6	16	7.8
RFU	7.2	23	6.7	21	10.0	7.4	21	7.0	20	10.6
INM	7.4	25	7.5	22	10.9	7.5	26	7.6	22	11.6
LSD ($P \leq 0.05$)										
Nutrient management	0.11[a]	2.1[a]	0.08[a]	1.8[a]	0.09[a]	0.13[a]	2.8[a]	0.07[a]	1.5[a]	0.14[a]

[a] significant

by cotton as affected by nutrient treatments, during first and fifth year was: FFU, 61 and 60 g ha^{-1} (overall mean, 62); RFU, 101 and 109 (overall mean, 107); and INM, 107 and 125 g ha^{-1} (overall mean, 120). In Shahpur soil, the impact of RFU and INM in enhancing Zn uptake was similar to Awagat soil; however, overall Zn uptakes were slightly greater because of slightly higher crop yields (Rafique et al. 2012) as well as plant Zn concentrations (Table 2). In Shahpur soil, total Zn uptake, during first and fifth year, was: FFU, 79 and 81 (overall mean, 76); RFU, 118 and 128 g ha^{-1} (overall mean, 117); INM, 125 and 142 g ha^{-1} (overall mean, 127).

Effects of nutrient management treatments on Zn uptake by wheat were similar to those on cotton ($P \leq 0.05$; Table 5); lowest Zn uptake by wheat was observed with FFU and maximum with INM. Also, with FFU total Zn uptake by wheat remained almost the same over the years, in both soils; and positive impacts of RFU and INM were more evident during the final phase of the experiment. Over the 5-year study period, INM resulted in 13 % more crop Zn uptake than RFU. In Shahpur soil, Zn uptake by wheat was relatively greater because of higher productivity potential of this soil (Rafique et al. 2012) as well as more plant tissue Zn concentrations (Table 3). Overall, wheat Zn uptake with INM was 10 % more than with RFU.

With recycled crop residue, Zn uptake by cotton crop was significantly enhanced during year-5 only, in both soils ($P \leq 0.05$; Table 4). In Awagat soil, recycled residue increased cotton Zn uptake by 20 % during the fifth year; overall increase was 17 g Zn $ha^{-1} year^{-1}$. Increase in Zn uptake was lower in Shahpur soil, i.e., 15 % during year-5, with an average increase of 15 g Zn $ha^{-1} year^{-1}$. Zinc uptake enhancement by wheat with crop residue recycling was sporadic; observed during year-2 in Awagat soil and during year-1 and year-4 in Shahpur soil ($P \leq 0.05$; Table 5). As in cotton, Zn uptake increases by wheat crop were lower in Shahpur soil.

This study also estimated fertilizer Zn use efficiency by the cotton-wheat system by considering enhanced Zn uptake by above-ground plant parts of both crops as a result of fertilizer Zn application to each cotton crop in the rotation (i.e., 5 kg Zn $ha^{-1} year^{-1}$ applied to cotton only). In accordance with lower total biomass of cotton (i.e., seed cotton, burs, leaves and stalks) than of wheat (i.e., grain and straw) (Rafique et al. 2012), total Zn uptakes were lower by cotton crop (Tables 4 and 5). And despite the fact that fertilizer Zn in RFU and INM treatments was applied to cotton only, fertilization-driven enhancements in total Zn uptake were more pronounced in case of wheat crop—revealing greater ability of wheat to utilize residual fertilizer Zn, even compared with fresh applied fertilizer Zn by cotton. Both cotton and wheat exhibited similar pattern of Zn uptake in both soils (Tables 4 and 5). Further studies are warranted to understand lower fertilizer Zn use efficiency by cotton compared to wheat.

Table 3 Five-year average Zn concentrations (mg kg^{-1}) in mature plant parts of wheat as affected by nutrient and crop residue management in two irrigated Aridisols. The values are means of four replicates

	Grain	Straw	Grain	Straw
	Awagat soil		Shahpur soil	
Flat bed site				
Without residue				
FFU	16	4.3	18	4.9
RFU	21	5.7	22	5.9
INM	22	5.9	23	6.1
With residue				
FFU	17	4.4	18	5.0
RFU	22	5.9	23	6.1
INM	23	6.1	24	6.3
Raised bed site				
Without residue				
FFU	17	4.4	19	4.9
RFU	22	5.8	23	6.0
INM	24	6.0	25	6.2
With residue				
FFU	18	4.6	19	5.1
RFU	23	6.0	24	6.2
INM	25	6.3	26	6.5
LSD ($P \leq 0.05$)				
Nutrient management	1.4[a]	0.09[a]	1.6[a]	0.11[a]

[a] significant

Soil Zn status

The surface soil Zn availability index (i.e., AB-DTPA extractable Zn) varied, in both soil types, with nutrient management treatments as well as with crop residue recycling ($P \leq 0.05$; Table 6). Whereas FFU treatment failed to maintain the initial soil Zn status after the growth of five cotton-wheat cycles, in both soils, RFU

Table 4 Total Zn uptake by cotton as affected by nutrient and crop residue management in two irrigated Aridisols. The values are means of two replicates

	Total Zn uptake (gha^{-1})											
	Year-1	Year-2	Year-3	Year-4	Year-5	Mean	Year-1	Year-2	Year-3	Year-4	Year-5	Mean
Flat bed sown cotton	Awagat soil						Shahpur soil					
Without crop residue												
FFU	56	57	55	55	52	55	76	69	62	69	72	69
RFU	87	93	91	93	90	91	105	98	88	103	111	101
INM	91	104	102	104	107	102	111	106	97	113	123	110
With crop residue												
FFU	60	63	62	63	58	61	77	76	69	77	82	76
RFU	91	99	102	109	103	101	112	106	98	115	123	111
INM	101	113	115	120	120	114	118	117	110	125	138	122
Raised bed sown cotton												
Without crop residue												
FFU	61	66	63	63	60	63	82	75	69	78	82	77
RFU	98	104	102	108	107	104	116	110	101	116	125	113
INM	104	116	116	123	120	116	121	120	109	129	140	124
With crop residue												
FFU	67	71	70	73	70	70	83	81	75	87	88	83
RFU	104	112	115	122	116	114	123	118	111	130	140	124
INM	111	125	130	138	132	127	131	128	120	142	154	135
LSD (P≤0.05)												
Nutrient management	8.9[a]	9.1[a]	11.0[a]	8.7[a]	8.5[a]	7.7[a]	8.4[a]	9.0[a]	10.8[a]	8.4[a]	9.9[a]	8.2[a]

[a] signifiant

and INM enhanced extractable Zn status. The enhancement was greater in Awagat soil, having lower initial Zn (0.48 mg Zn kg^{-1}) compared with Shahpur soil (0.72 mg Zn kg^{-1}). In Awagat soil, increases in soil Zn status ranged from 4 % with RFU to 22 % with INM over initial soil Zn; the overall increases in soil Zn of Shahpur soil were lower, i.e., 6 % with RFU and 16 % with INM over the initial Zn status. Soil-incorporated crop residue also enhanced surface soil Zn status by 14 % in Awagat soil and by 7 % in Shahpur soil. However, despite more cotton yields on raised beds (Rafique et al. 2012), soil Zn status did not differ between the flat-bed plot sites and the raised-bed plot sites within the experimental fields (Table 6).

Apparent soil Zn balances

This cotton-wheat field study revealed that apparent soil Zn balances were positive under all tested nutrient management strategies, including FFU (Table 7). Though maximum soil Zn gains over the 5-year period, in both soil types, were observed with INM (i.e., +25.81 kg Zn ha^{-1} in Awagat soil and +25.79 kg Zn ha^{-1} in Shahpur soil), soil Zn balances were positive even in the absence of fertilizer Zn use under the FFU regime (i.e., +0.66 kg Zn ha^{-1} in Awagat soil and +0.62 kg Zn ha^{-1} in Shahpur soil) which failed to optimize crop yields (Rafique et al. 2012) because of imbalanced nutrient supplies. Over the 5-year period, the recycled crop residue contributed 0.28–0.59 kg Zn ha^{-1} in Awagat soil and 0.38–0.65 kg Zn ha^{-1} in Shahpur soil. Thus, crop residue turn over in the soils resulted in greater positive soil Zn balances (i.e., +0.35 kgha^{-1} in Awagat soil and +0.44 kgha^{-1} in Shahpur soil) compared with the respective without residue treatments (P≤0.05). On an average, lower positive balance by about 0.10 kg Zn ha^{-1} was observed at raised-bed plot sites compared with the flat-bed plot sites within the same field (Table 7).

Table 5 Total Zn uptake by wheat as affected by nutrient and crop residue management in two irrigated Aridisols. The values are means of four replicates

	Total Zn uptake (gha^{-1})											
	Year-1	Year-2	Year-3	Year-4	Year-5	Mean	Year-1	Year-2	Year-3	Year-4	Year-5	Mean
Flat bed sites	Awagat soil						Shahpur soil					
Without crop residue												
FFU	70	69	65	68	63	67	98	103	95	101	103	100
RFU	115	118	120	111	117	116	141	149	143	153	161	149
INM	123	127	130	121	128	126	144	163	152	164	172	159
With crop residue												
FFU	75	75	73	78	75	75	99	108	103	105	113	106
RFU	124	127	133	125	132	128	148	155	159	167	173	160
INM	130	136	148	144	144	140	152	174	164	182	189	172
Raised bed sites												
Without crop residue												
FFU	73	74	69	74	72	73	100	114	101	107	109	106
RFU	112	126	131	125	131	125	141	152	152	163	176	157
INM	121	134	141	138	148	136	150	169	157	180	189	169
With crop residue												
FFU	76	81	80	84	82	81	102	117	109	118	116	112
RFU	124	136	145	142	147	139	151	166	165	179	188	170
INM	134	147	156	158	167	152	155	180	175	193	202	181
LSD ($P\leq0.05$)												
Nutrient management	6.4[a]	4.5[a]	9.9[a]	7.2[a]	9.6[a]	3.9[a]	5.4[a]	6.0[a]	6.1[a]	9.9[a]	6.2[a]	3.0[a]

[a] significant

Discussion

Crop productivity, plant Zn status and total Zn uptake

In both soils, Zn concentration in diagnostic leaves of cotton and wheat varied with experimental treatments (Fig. 1). Zinc concentrations were greater in heavier-textured Shahpur soil than in coarse-textured Awagat soil. In contrast, in Awagat soil, magnitudes of crop Zn concentration increase with improved nutrient managements were greater than in Shahpur soil. As the suggested sufficiency range of Zn concentration in diagnostic leaves of cotton is 20–200 $mgkg^{-1}$ and of wheat is 20–70 $mgkg^{-1}$ (Jones et al. 1991; Reuter et al. 1997), in our study average leaf Zn concentrations in diagnostic leaves of both crops attained with FFU, in both soils (i.e., cotton, 18–21 $mgkg^{-1}$; wheat, 15–18 $mgkg^{-1}$), were within the deficient ranges (Jones et al. 1991; Reuter et al. 1997). The RFU and INM treatments not only increased crop yields (Rafique et al. 2012) but also enhanced crop leaf Zn concentrations to adequate levels (Fig. 1). Zinc concentrations were greater in heavier-textured Shahpur soil than in coarse-textured Awagat soil. In contrast, magnitudes of increases in leaf Zn concentration with improved nutrient managements were greater in Awagat soil.

Both the improved nutrient management strategies, i.e., RFU and INM, enhanced yield of both crops, over the yields obtained with the FFU practice (Rafique et al. 2012). Maximum crop yields and Zn uptakes by cotton and wheat were obtained with INM, i.e., recommended fertilizer use plus FYM. As FYM not only provides a supply of macro- and micro-nutrients (Kabeerathumma et al. 1993) but also improves soil physical condition (Kurual and Tripathi 1990; Bhattacharyya et al. 2004; Mahmood-ul-Hassan et al. 2012) and enhances soil microbial activities (Tiwari et al. 1998), maximization of crop productivity with combined use of fertilizers and organic manure is understandable. Crop productivity trends over the

Table 6 Mean zinc status of surface soils (0–15 cm), at termination of 5-year experiment, as affected by nutrient and crop residue management in two irrigated Aridisols

	AB-DTPA extractable soil Zn ($mgkg^{-1}$)	
	Awagat soil	Shahpur soil
Initial	0.48	0.72
Flat bed site		
Without residue		
FFU	0.40	0.68
RFU	0.46	0.72
INM	0.52	0.79
With residue		
FFU	0.44	0.72
RFU	0.52	0.78
INM	0.58	0.84
Raised bed sites		
Without residue		
FFU	0.39	0.70
RFU	0.46	0.75
INM	0.53	0.84
With residue		
FFU	0.45	0.74
RFU	0.54	0.82
INM	0.60	0.90
LSD (P≤0.05)		
Nutrient management	0.05[a]	0.05[a]

[a] signifiant

years (Rafique et al. 2012) clearly revealed that FFU was inadequate to optimize crop productivity. Earlier researchers have also observed that Zn use is needed to optimize irrigated cotton and wheat productivity in such alluvial calcareous soils of Pakistan (Ahmed et al. 2010, 2011).

The yield-increasing effect of INM became more pronounced as the experiment progressed over years. Obviously, FYM use for each crop left a beneficial residual effect, which accumulated with its 10 applications over 5 years. According to the soil test diagnostic criteria suggested by Soltanpour (1985), both the soils were deficient in SOM, N, P, Zn (AB-DTPA Zn 0.48 and 0.72 $mgkg^{-1}$) and B (Table 1). Continuous application of the deficient nutrients at recommended rates (i.e., RFU and INM) most probably rectified the diagnosed soil nutrient deficiencies, resulting in appreciable crop growth and yield improvements, after 2–3 years (Rafique et al. 2012). At the end of 5-year experiment, maximum SOM level was 0.74 % in Awagat soil and 0.93 % in Shahpur soil; the corresponding soil Zn levels were 0.60 $mgkg^{-1}$ and 0.90 $mgkg^{-1}$ indicating slight buildups of SOM and soil Zn with improved nutrient managements coupled with crop residue recycling. In the present study, greater cumulative beneficial impact of INM in the coarse-textured Awagat soil is attributed to its lower native SOM content (i.e., 0.60 %) than in the finer-textured Shahpur soil with initial SOM 0.85 % (Xie and MacKenzie 1986).

Progressive year to year increases in crop Zn uptake with RFU and INM (Tables 3 and 4) are attributed to consistent increases in yields over the five-year study period, except for a sharp cotton yield decline in Shahpur soil during year-3 (Rafique et al. 2012). Thus, higher crop yields, as a consequence of improved nutrient management, resulted in greater crop Zn uptakes.

In this study, crop residue recycled back to the soil also led to enhanced Zn uptakes by both crops, especially during the final year of the experiment. Crop residues and organic manures, on decomposition, not only deliver nutrients for plants and soil microbial communities but also are a source of energy for soil microbes, which in turn, may promote soil nutrient replenishment (Bielders et al. 2002).

Changes in soil Zn status

Over the 5-year period, with FFU a slight but gradual decline in soil Zn availability was observed in both soil types (Table 6). However, soil Zn status was enhanced with RFU, and was maximized with INM (where 25 %N was supplied through FYM). Strong positive relationships between AB-DPTA soil Zn and yield of both cotton and wheat in both soil types (Fig. 2) revealed that increases in crop yields were related to soil Zn availability. Thus, gradual decline of soil Zn availability during the five-year study period with FFU, without crop residue recycling (Table 6), indicated that soil Zn deficiency may be contributing towards crop yield stagnation or even slight yield declines. Lower enhancement in Zn status of Shahpur soil with RFU and INM (Table 6) is attributed to more Zn fixation in this heavier textured, higher free lime-containing Aridisol (Rafique et al. 2012). Our results are in agreement with earlier studies suggesting more Zn fixation in heavier and more lime-rich soils (Hussain and Rashid 1979; Mahmood-ul-Hassan et al.

Table 7 Apparent soil zinc balances, at termination of 5-year experiment, as affected by nutrient and crop residue management in two irrigated Aridisols

	Crop res.	5-year input[1]	5-year Crop uptake	Apparent balance	Crop res.	5-year input[1]	5-year Crop uptake	Apparent balance
	Apparent zinc balance (kg Zn ha^{-1})							
	Awagat soil				Shahpur soil			
Flat bed								
Without residue								
FFU		1.26	0.61	0.65		1.41	0.85	0.56
RFU		26.26	1.03	25.23		26.41	1.25	25.16
INM		26.86	1.14	25.72		27.01	1.34	25.67
With residue								
FFU	0.28	1.54	0.68	0.86	0.38	1.79	0.91	0.88
RFU	0.48	26.74	1.15	25.59	0.55	26.96	1.36	25.60
INM	0.54	27.40	1.27	26.13	0.61	27.62	1.47	26.15
Raised beds								
Without residue								
FFU		1.12	0.68	0.44		1.27	0.92	0.35
RFU		26.12	1.14	24.98		26.27	1.35	24.92
INM		26.72	1.26	25.46		26.87	1.46	25.41
With residue								
FFU	0.31	1.43	0.75	0.68	0.40	1.67	0.97	0.70
RFU	0.53	26.65	1.26	25.39	0.60	26.87	1.47	25.40
INM	0.59	27.31	1.40	25.91	0.65	27.52	1.58	25.94
LSD ($P \leq 0.05$)								
Nutrient management	0.02[a]	1.4[a]	0.03[a]	1.7[a]	0.02[a]	1.6[a]	0.02[a]	1.5[a]

1 Zn input: Fertilizer (in BNM & INM treatments), 25.0 kgha^{-1} ; FYM, 0.60 kgha-1; Irrigation water (all treatments)—flat bed, 1.12 and 1.32 kgha^{-1} ; raised beds, 0.98 and 1.18 kgha^{-1} ; rainfall (all treatments), 0.14 and 0.09 kgha^{-1} in Awagat and Shahpur soil

[a] significant

2008). Therefore, use of fertilizer Zn, preferably in conjunction with organic manures, such as FYM, is suggested for sustaining productivity of cotton-wheat cropping system in light to medium textured irrigated Aridisols.

Apparent soil Zn balances

Our estimates of Zn inputs and outputs for arriving at apparent soil Zn balances indicate that variations in Zn balances were predominantly related to applied fertilizer Zn and only slightly to other sources of Zn input (i.e., irrigation water, FYM, crop residue) and Zn removal through crop uptake. Removal of a nutrient (export from the field) depends on crop yield level, soil type (productivity potential, soil chemistry, etc.), and recycling or removal of crop residues from the field (Yadvinder-Singh et al. 2005). In our study, apparent Zn balances in both soils over the 5-year period were positive with all nutrient management treatments, including FFU (Table 7). Mean crop Zn uptake was lowest with FFU practice (i.e., 0.66 kg Zn ha^{-1} in Awagat soil and 0.62 kg Zn ha^{-1} in Shahpur soil) because of lowest crop biomass production (Rafique et al. 2012) as well as low plant part Zn concentrations with this treatment (Tables 2 and 3). Maximum soil Zn gain of 25.80 kg Zn ha^{-1} with INM, which was almost equal in both soils, was probably a consequence of Zn addition through FYM which added 0.60 kg Zn ha^{-1} in each soil during the five-year period, over and above of 25.0 kgha^{-1} fertilizer Zn (Table 7). The AB-

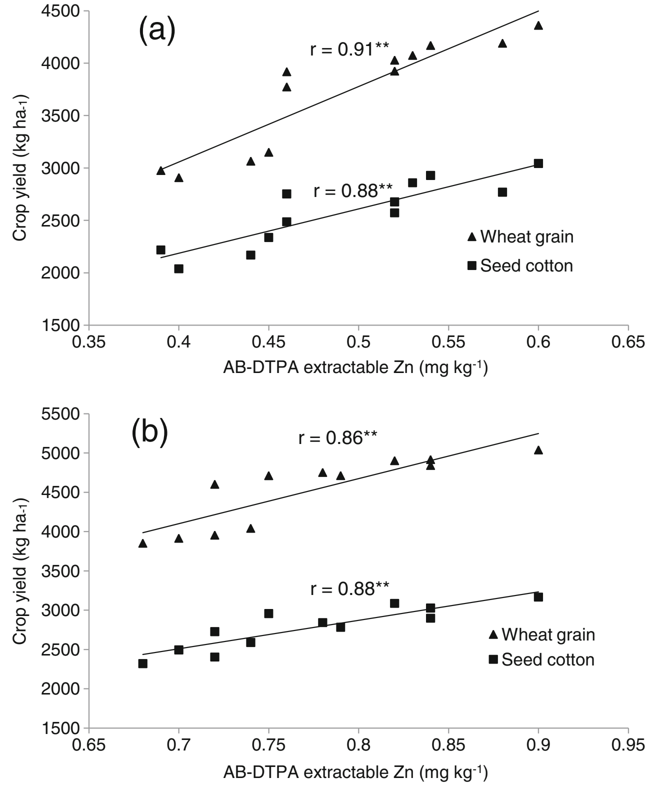

Fig. 2 Relationship between AB-DTPA extractable soil Zn and crop yield, as affected by nutrient management treatments (5-year means), in Awagat **a** and Shahpur **b** soils

DTPA extractable soil Zn contents determined at termination of the field experiment revealed maximum soil Zn build-up with INM treatment (i.e., 0.56 $mgkg^{-1}$ in Awagat soil and 0.84 $mgkg^{-1}$ in Shahpur soil). Appreciable build-ups of soil Zn with RFU and INM, despite higher crop Zn uptakes with these treatments, is understandable because crop removals were meager (i.e., 0.062–0.170 kg Zn ha^{-1}) compared with substantial Zn additions through fertilizer, crop residue, etc. (i.e., 26.12–27.40 kg Zn ha^{-1}). Greater Zn balances with residue recycling were the result of Zn additions through plant residues. Slightly lower positive Zn balances observed in raised bed plots compared with flat beds (Table 7) are attributed to greater Zn removal in more biomass of cotton grown at the raised beds (Rafique et al. 2012).

Zinc use efficiency by crops

In our estimation, use efficiency of fertilizer Zn by cotton, in all nutrient treatments, was extremely low, i.e., 0.72–1.06 %: i.e., Awagat soil—RFU, 0.82 %; INM, 1.06 %; Shahpur soil—RFU, 0.72 %; INM, 0.94 %. Fertilizer Zn use efficiency by wheat was slightly higher, i.e., 1.06–1.30 %: Awagat soil—RFU, 1.06 %; INM, 1.30 %; Shahpur soil—RFU, 1.06 %; INM, 1.28 %. Over the 5-year period, mean annual fertilizer Zn use efficiency by the cotton-wheat system was 1.78–2.36 %: i.e., Awagat soil—RFU, 1.88 %; INM, 2.36 %; Shahpur soil—Awagat soil, 1.78 %; Shahpur soil, 2.22 %. As ~98 % of the applied fertilizer Zn was left unutilized (fixed/sorbed and precipitated) in the soils, succeeding crops in the rotation benefit from the residual Zn. Similar findings of beneficial residual effect of fertilizer Zn on succeeding crops has been reported by many earlier researchers. For example, Brennan (2005) calculated that a single application of 0.75 kg Zn ha^{-1}, when applied to low-Zn sandy loam soils in south-west Australia, would support as few as six and up to an infinite number of wheat crops depending on crop yield, Zn sorption capacity of the soils, and the presence of Zn impurities in P fertilizers. Therefore, Bell and Dell (2008) have stated that the amount of Zn required by crops (as fertilizer) is small compared with the amount of Zn recovered in the first crop. In consideration of very small Zn uptakes by cotton and wheat crops in the present study (Tables 4 and 5), compared with a high fertilizer rate of 5 kg Zn ha^{-1}, even one-time application of a lower fertilizer Zn rate may prove adequate for several cotton-wheat rotation in irrigated Aridisols. However, *in situ* long term field studies are warranted to arrive at actual long-term Zn fertilization needs of this cropping system.

Zinc use efficiency from organic sources appears to be much greater. For example, based on the additional Zn uptake from the Zn returned to soil in crop residue (Table 7), about 24 % of the residue Zn was taken up in Awagat soil and 13-21 % in Shahpur soil. Similarly, the recovery of Zn input from the FYM (Table 7) was 18-21 % in the Awagat soil and 15-18 % in Shahpur soil. Though >75 % of the total Zn added to the soils by organic sources was retained in the soils, Zn use efficiency from the organic sources was much greater than from the fertilizer Zn. However, total Zn input by both the organic sources (i.e., crop residue and FYM) was inadequate to cater to the crop Zn requirements. Thus, fertilizer Zn use is required to optimize crop productivity.

Conclusions

Apparent soil Zn balances were positive even in the absence of fertilizer Zn use. Also, as crop Zn uptakes are very low, crop use efficiency of fertilizer Zn per annum was around 2 % of the applied Zn dose. Thus, fertilizer Zn leaves a beneficial residual effect for the succeeding crops.

Obviously, the FFU practice for the cotton-wheat cropping system is not only responsible for crop yield stagnation but may also lead to progressive yield declines and soil resource degradation. Though RFU proved quite effective in replenishing soil Zn fertility and enhancing cotton-wheat productivity, INM, coupled with nutrient recycling through soil-incorporation of crop residue, holds greater promise in attaining better soil Zn fertility and crop productivity while sustaining the soil resource base. Whereas apparent soil N, P, K balances are considered useful for predicting fertilizer requirements, such information for Zn appears to be of little value in this regard. High soil Zn sorption, rather than low total Zn in the soil, appears to be responsible for this ambiguity. Therefore, soil testing and plant analysis remain necessary tools for diagnosing Zn deficiency in the cropping system (Rashid and Ahmed 1994; Rafique et al. 2006; Ahmed et al. 2010).

Acknowledgements We are grateful to Ministry of Science & Technology, Government of Pakistan for the financial support through Pak-Kazakh Joint Research Fund Project, to Central Cotton Research Institute, Multan and Pak-German Institute for Cooperative Agriculture, Multan for invaluable support in this challenging field-research endeavor, to Prof. Dr. M. Inayat Khan and Mr. M. Asif Ghumman for support in experimental design and statistical work and to Mr. M. Tauseef Tabassum and Mr. Zulfqar Ali for assistance in analytical work. Also, we are grateful to the anonymous reviewers for their constructive suggestions which helped in improvement of the manuscript.

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