

# Effect of zinc sulphate application and the cyclic incorporation of cereal straw on yields, the tissue concentration and uptake of Zn by crops and availability of Zn in soil under rice–wheat rotation

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## Abstract

**Background** Soil incorporation of cereal straw to avoid burning and air pollution may influence the availability of Zn, a critical micronutrient in cereal production. Field experiment was carried out to evaluate the effect of zinc sulphate application and the cyclic incorporation of cereal straw on the yields, tissue concentration and uptake of Zn by rice and wheat crops and availability of Zn in soil.

**Results** Application of 25 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the grain yields of rice by 24.3 and 56.3 % over control during I and II year, respectively. Application of 25 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop + cyclic incorporation of 1.5 t straw ha<sup>-1</sup> increased the grain yields of rice by 21.4 and 87.4 % over control during I and II year, respectively. In I year, the grain yield of wheat crop was not significantly influenced by the different treatments while in II year the highest wheat grain yield was recorded with 25 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop + cyclic incorporation of 6.0 t cereal straw ha<sup>-1</sup>. Application of 25 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice + cyclic incorporation of 1.5 t straw ha<sup>-1</sup> resulted in a significant increase in the concentration of Zn in the plant tissues of both rice and wheat crops. The cyclic incorporation of 1.5–3.0 t cereal straw ha<sup>-1</sup> maintained better availability of ZnSO<sub>4</sub> applied to I year rice crop to the subsequently grown crops.

**Conclusion** Soil application of 25 kg ZnSO<sub>4</sub> along with incorporation of 1.5 t cereal straw ha<sup>-1</sup> prior to I year rice

transplanting followed by cyclic incorporation of cereal straw in subsequent crops ensures higher availability of Zn in soil and higher yields in rice–wheat rotation.

**Keywords** Crop residue management · DTPA-extractable Zn · Rice–wheat rotation

## Introduction

Zinc deficiency is a worldwide problem in crop production and a serious problem, especially in rice croplands of Asia (Tisdale et al. 1997). Usually, soil application of 25.0–50.0 zinc sulphate heptahydrate ha<sup>-1</sup> is done to correct the deficiency; however, the availability of soil applied Zn is very poor and declines with time (Srivastava et al. 2008). It has been reported that application of 5–10 t organic manure ha<sup>-1</sup> to rice–wheat rotation adds useful organic matter to the soil (Meelu and Morris 1988) and reduces the requirement of Zn fertilizers by 50 % (Sakal et al. 1985). However, owing to increasing mechanization in agriculture the population of farm cattle has declined and the availability of organic manures to the farmers in Asia is very poor. A major issue for the sustainability of agricultural systems in the developing countries is the management of soil organic matter through the rational use of organic inputs such as animal manures, industrial wastes, green manures, and crop residues (Singh et al. 1986; Powlson 1994). The use of industrial wastes as a substitute of organic manure is also limited due to the possible presence of toxic organic and inorganic constituents in these materials. This leaves recycling of crop residues as one of the easiest option to ensure the conservation of soil organic matter and help reducing the dependence on chemical fertilizers. Rice–wheat cropping system is one of the most widely practiced system covering about 12 million ha area in India alone

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(Prasad et al. 2000). A considerable area under rice and wheat is now mechanically harvested using combine harvesters. The crop residues left in the field after the harvesting are generally burnt by the farmers to facilitate the seedbed preparation and seeding of the subsequent crop. This leads to twin problems of the loss of useful plant nutrients and the pollution of air (Hanafi et al. 2012). Application of chemical fertilizers supplying only N, P and K to rice–wheat rotation has undoubtedly increased the production of food grain in the past decades in many Asian countries, but simultaneously it has also led to the emergence of some additional nutrient deficiencies particularly, of micronutrients like Zn in soils. With the recycling of crop residues in rice–wheat rotation, a part of Zn taken up by the previous crop could be recycled back to the soil to partly reduce the dependence on chemical zinc fertilizer. Besides this, the organic acids produced during the decomposition of incorporated cereal residues might also improve the availability of Zn in the soil. The present investigation was conducted to study the effect of zinc sulphate application with or without cyclic incorporation of cereal straw on the yields, Zn concentration and uptake by crops and the contents of DTPA-extractable Zn in the soil under rice–wheat rotation.

**Materials and methods**

**Field experiments**

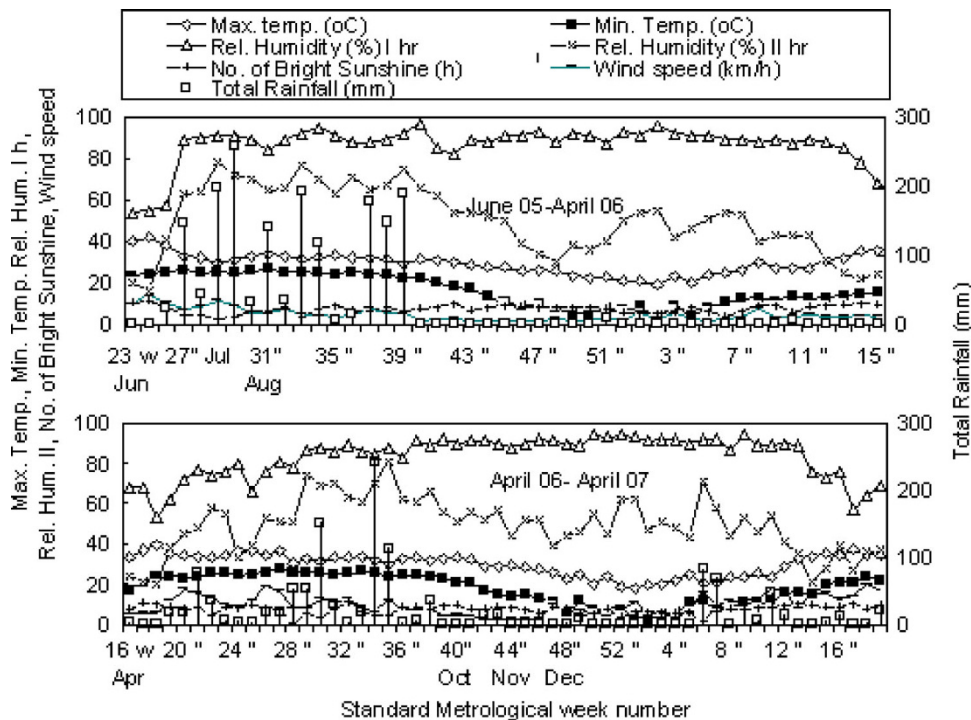
A field experiment was conducted during 2005–2007 at Crop Research Centre, Govind Ballabh Pant University of

Agriculture and Technology, Pantnagar, District Udham Singh Nagar, India, situated at 29°N latitude, 79.3°E longitude and 243.8 m above the mean sea level in the foothills of Shivalik range of Himalaya. The meteorological data recorded during the experimental period are depicted in Fig. 1. The soil of experimental site is derived from calcareous alluvium which occurs in gentle to moderately sloping areas of the higher and better drained portion of the land. It has been classified as Typic Hapludoll. The general properties of the experimental soil such as soil texture by Bouyocous hydrometer method, soil pH and E.C. (1:2 soil water suspension), readily oxidizable organic C by Modified Walkley and Black method and 0.005 M diethylene triamine pentaacetic acid (DTPA, pH 7.3) extractable micronutrient cations (Lindsay and Norvell 1978) by atomic absorption spectrophotometry (Model GBC-Avanta M) were determined following the procedures outlined by Page et al. (1982).

The experimental soil had a loam texture, 7.01 pH and 0.278 dS m<sup>-1</sup> EC in 1:2 soil water suspension, 10.3 g organic carbon and DTPA-extractable 0.57 mg Zn; 1.24 mg Cu; 25.39 mg Fe and 5.79 mg Mn kg<sup>-1</sup> soil.

The experiment was conducted in a randomized block design with a unit plot size of 3.25 m × 2.75 m. The treatments which were imposed to I rice crop (2005–2006) included: control (Z<sub>0</sub> S<sub>0</sub>), 6.25 kg ZnSO<sub>4</sub> ha<sup>-1</sup> (Z<sub>6.25</sub> S<sub>0</sub>), 12.5 kg ZnSO<sub>4</sub> ha<sup>-1</sup> (Z<sub>12.5</sub> S<sub>0</sub>), 25.0 kg ZnSO<sub>4</sub> ha<sup>-1</sup> (Z<sub>25.0</sub> S<sub>0</sub>), 1.5 t straw ha<sup>-1</sup> (Z<sub>0</sub> S<sub>1.5</sub>), 6.25 kg ZnSO<sub>4</sub> + 1.5 t cereal straw ha<sup>-1</sup> (Z<sub>6.25</sub> S<sub>1.5</sub>), 12.5 kg ZnSO<sub>4</sub> + 1.5 t cereal straw ha<sup>-1</sup> (Z<sub>12.5</sub> S<sub>1.5</sub>), 25.0 kg ZnSO<sub>4</sub> + 1.5 t cereal

**Fig. 1** Metrological parameters during crop seasons of the experiment



straw  $\text{ha}^{-1}$  ( $Z_{25.0} S_{1.5}$ ), 3.0 t cereal straw  $\text{ha}^{-1}$  ( $Z_0 S_{3.0}$ ), 6.25 kg  $\text{ZnSO}_4$  + 3.0 t cereal straw  $\text{ha}^{-1}$  ( $Z_{6.25} S_{3.0}$ ), 12.5 kg  $\text{ZnSO}_4$  + 3.0 t cereal straw  $\text{ha}^{-1}$  ( $Z_{12.5} S_{3.0}$ ), 25.0 kg  $\text{ZnSO}_4$  + 3.0 t cereal straw  $\text{ha}^{-1}$  ( $Z_{25.0} S_{3.0}$ ), 6.0 t cereal straw  $\text{ha}^{-1}$  ( $Z_0 S_{6.0}$ ), 6.25 kg  $\text{ZnSO}_4$  + 6.0 t cereal straw  $\text{ha}^{-1}$  ( $Z_{6.25} S_{6.0}$ ), 12.5 kg  $\text{ZnSO}_4$  + 6.0 t cereal straw  $\text{ha}^{-1}$  ( $Z_{12.5} S_{6.0}$ ), and 25.0 kg  $\text{ZnSO}_4$  + 6.0 t cereal straw  $\text{ha}^{-1}$  ( $Z_{25.0} S_{6.0}$ ). In I year, wheat straw was incorporated in the soil at 30 days before the transplanting of I year rice crop as specified for a given treatment. In order to facilitate the decomposition of incorporated wheat straw, the calculated amounts of N for the different levels of wheat straw were also applied as urea to bring down the C:N of straw to 20:1. Zinc sulphate heptahydrate (fertilizer grade, 21 % Zn) was applied by broadcasting as specified for a given treatment before the puddling operation for I year rice crop. A basal dose of 60 kg  $\text{P}_2\text{O}_5$  as single super phosphate and 40 kg  $\text{K}_2\text{O}$  as muriate of potash was uniformly applied to each plot. Nitrogen falling short of a uniform basal dose of 75 kg N  $\text{ha}^{-1}$  was calculated for each treatment by deducting the amount of N initially added along with the wheat straw and it was applied basally as urea. Twenty-three-day-old seedlings of rice (cv. PD-4) were transplanted at row-to-row spacing of 20 cm and plant-to-plant distance of 10 cm in each plot. The remaining half amount of nitrogen (75 kg N  $\text{ha}^{-1}$ ) was top dressed in two equal splits at 30 and 60 days after transplanting of rice. All the plots were kept submerged by maintaining 5–7 cm water level over soil surface up to the milk stage.

After the harvest of I year rice crop, the required quantity of rice straw as specified for the treatment was incorporated in the soil at 30 days prior to the sowing of wheat. The calculated amounts of N for different levels of rice straw were applied as urea to bring down the C:N of straw to 20:1. All the plots were manually dug and prepared for the sowing of wheat crop. A basal dose of N, P and K was applied as mentioned for I year rice crop. Wheat (cv. UP-2425) seeds were sown keeping row-to-row distance of 15 cm and plant-to-plant distance of 2–3 cm. Top dressing of remaining 75 kg N as urea  $\text{ha}^{-1}$  was done in two equal splits at 22 and 60 days after the sowing of wheat crop. Five irrigations were given to wheat crop at all critical growth stages of the crop.

In II year (2006–2007), rice and wheat crops were grown with the incorporation of specified quantities of straw of previous crop as mentioned for the I year.

The flag leaves ( $n = 20$ ) of both rice and wheat crops were collected from each plot in both the years. At maturity, the crops were harvested and the threshed grains from the net plot area (2 m  $\times$  2 m) were cleaned, weighed and finally expressed in t  $\text{ha}^{-1}$ . The straw yields were also recorded from net plot area and expressed in t  $\text{ha}^{-1}$ .

## Disease score

In II year (2006–2007), rice crop was infected by brown spot disease caused by *Cochliobolus miyabeanus* (Ito and Kuribayashi) Drechsler ex Dastur. The symptoms were recorded on five randomly selected plants from each plot. On the basis of the mean percent affected area on leaves, a disease score was assigned as: 0 = no incidence, 1 = less than 1 %, 2 = 1–3 %, 3 = 4–5 %, 4 = 6–10 %, 5 = 11–15 %, 6 = 16–25 %, 7 = 26–50 %, 8 = 51–75 % and 9 = 76–100 % (International Rice Research Institute 1996). An average of disease score was computed for each plot.

## Chemical analysis of plant and soil samples

The samples of flag leaves, grains and straw of both rice and wheat collected from each plot were washed thoroughly first in tap water, then in 0.1 N HCl and finally in distilled water before drying them in an electric oven at 60 °C. Finely ground samples (0.5–1 g) of flag leaves, grains and straw were digested in di-acid ( $\text{HNO}_3:\text{HClO}_4$ , 3:1 v/v) and analyzed for Zn by atomic absorption spectrophotometry (Model GBC-Avanta M).

Surface (0–15 cm) soil samples were collected from each plot after the harvest of wheat crop in both the years. Soil samples were analyzed for the DTPA-extractable micronutrient cations (Lindsay and Norvell 1978) by atomic absorption spectrophotometry.

## Statistical analysis

The data were analyzed for variance following the procedure outlined by Snedecor and Cochran (1967). The significance of variance was tested at  $p \leq 0.05$ .

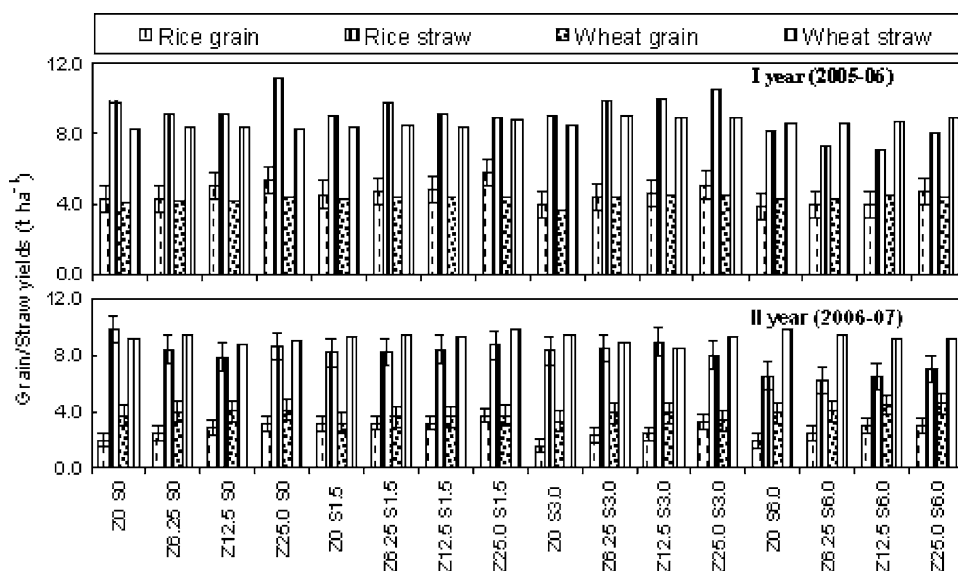
## Results and discussion

### Grain and straw yields

The data on the effect of different levels of zinc sulphate applied to I year rice crop and the cyclic incorporation of cereal straw on the grain and straw yields of rice and wheat crops are presented in Fig. 2. Application of 25.00 kg  $\text{ZnSO}_4$   $\text{ha}^{-1}$  to I year rice crop increased the grain yield of rice significantly by 24.3 % over control. The response of Zn application to rice crop had been reported by several workers (Saravanan and Ramnathan 1988; Channabasavanna et al. 2001). Among other treatments, a combined application of 25.00 kg zinc sulphate + 1.5 t wheat straw  $\text{ha}^{-1}$  to I year rice crop increased the grain yield of rice significantly by 35.3 % over control. Neither the



**Fig. 2** Effect of different levels of zinc sulphate applied to I year rice crop and cyclic incorporation of cereal straw on the grain and straw yields of rice and wheat in 2005–2006 and 2006–2007. Vertical bars C.D. at  $p \leq 0.05$



application of any level of ZnSO<sub>4</sub> nor the incorporation of any level of wheat straw had statistically significant effect on the straw yields of I year rice crop.

Both the grain and straw yields of I year wheat crop were not significantly influenced by the different levels of zinc sulphate applied to I year rice crop with or without the cyclic incorporation of cereal straw.

During the II year (2006–2007), the rice crop was infested by the brown spot disease. The II year rice crop season had poor and ill-distributed rainfall (Fig. 1). The residual effect of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop increased the grain yields of II year rice significantly by 45.8 and 56.3 % over control, respectively. A relatively higher residual effect of ZnSO<sub>4</sub> applied to I year rice crop on the grain yields of II year rice crop as compared to the direct effect noted during I year could be ascribed to a severe brown spot infestation in control plots which led to very low rice grain yields in control. The cyclic incorporation of 1.5 t straw ha<sup>-1</sup> increased the grain yield of II rice crop significantly by 56.3 % over control. However, the cyclic incorporation of higher rates of straw (3.0 and 6.0 t ha<sup>-1</sup>) failed to alter the grain yields of II year rice crop significantly in comparison to control. The treatments involving the residual effect of 6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 1.5 t straw ha<sup>-1</sup> increased the grain yield of II year rice crop by 60.4, 60.4 and 87.5 % over control, respectively. Similarly, the residual effect of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 3.0 t straw ha<sup>-1</sup> increased the grain yield of II year rice crop by 64.6 % over control. The residual effect of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 6.0 t straw

ha<sup>-1</sup> increased the grain yield of II year rice crop by 50.0 and 52.1 % over control, respectively.

The straw yields of II year rice crop under different treatments were significantly decreased in comparison to control except for the treatment involving the residual effect of 12.50 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 3.0 t straw. Higher straw yield of II year rice under control as compared to other treatments could be attributed to the serious attack of brown spot disease which led to the premature drying and poor grain bearing in the control plots.

In II year (2006–2007), the grain yield of wheat crop was significantly influenced by the different treatments. The residual effect of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 6.0 t straw ha<sup>-1</sup> increased the grain yield of II wheat crop significantly by 20.0 and 22.2 % over control, respectively. An increase in the grain yields of wheat due to Zn application had been reported earlier by Nambiar (1992) and Agrawal and Bhan (1997).

#### Brown spot disease score in II rice crop

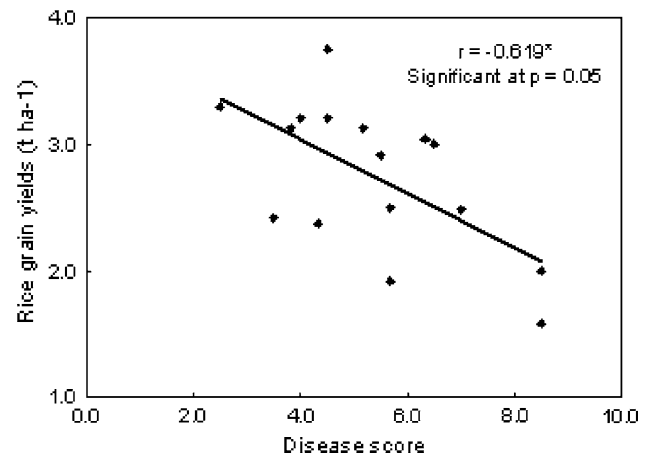
The data pertaining to the disease score of brown spot in II rice crop under different treatments are presented in Table 1. The highest disease score (8.5) was noted in control as well as in the treatment receiving cyclic incorporation of 3 t straw ha<sup>-1</sup> in every crop season. The residual effect of 6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop decreased the disease score significantly by 33.3, 35.3 and 54.9 % in comparison to control, respectively. Zinc application has been shown to reduce many plant diseases caused by fungi, e.g., *Fusarium*

**Table 1** Effect of different levels of zinc sulphate applied to I year rice crop and cyclic incorporation of cereal straw on the brown spot disease score of II year rice crop (2006–2007)

Treatments	Disease score
Control (Z <sub>0</sub> S <sub>0</sub> )	8.50
6.25 kg ZnSO <sub>4</sub> ha <sup>-1</sup> (Z <sub>6.25</sub> S <sub>0</sub> )	5.67
12.5 kg ZnSO <sub>4</sub> ha <sup>-1</sup> (Z <sub>12.5</sub> S <sub>0</sub> )	5.50
25.0 kg ZnSO <sub>4</sub> ha <sup>-1</sup> (Z <sub>25.0</sub> S <sub>0</sub> )	3.83
1.5 t straw ha <sup>-1</sup> (Z <sub>0</sub> S <sub>1.5</sub> )	5.17
6.25 kg ZnSO <sub>4</sub> + 1.5 t straw ha <sup>-1</sup> (Z <sub>6.25</sub> S <sub>1.5</sub> )	4.00
12.5 kg ZnSO <sub>4</sub> + 1.5 t straw ha <sup>-1</sup> (Z <sub>12.5</sub> S <sub>1.5</sub> )	4.50
25.0 kg ZnSO <sub>4</sub> + 1.5 t straw ha <sup>-1</sup> (Z <sub>25.0</sub> S <sub>1.5</sub> )	4.50
3.0 t straw ha <sup>-1</sup> (Z <sub>0</sub> S <sub>3.0</sub> )	8.50
6.25 kg ZnSO <sub>4</sub> + 3.0 t straw ha <sup>-1</sup> (Z <sub>6.25</sub> S <sub>3.0</sub> )	4.33
12.5 kg ZnSO <sub>4</sub> + 3.0 t straw ha <sup>-1</sup> (Z <sub>12.5</sub> S <sub>3.0</sub> )	3.50
25.0 kg ZnSO <sub>4</sub> + 3.0 t straw ha <sup>-1</sup> (Z <sub>25.0</sub> S <sub>3.0</sub> )	2.50
6.0 t straw ha <sup>-1</sup> (Z <sub>0</sub> S <sub>6.0</sub> )	5.67
6.25 kg ZnSO <sub>4</sub> + 6.0 t straw ha <sup>-1</sup> (Z <sub>6.25</sub> S <sub>6.0</sub> )	7.00
12.5 kg ZnSO <sub>4</sub> + 6.0 t straw ha <sup>-1</sup> (Z <sub>12.5</sub> S <sub>6.0</sub> )	6.50
25.0 kg ZnSO <sub>4</sub> + 6.0 t straw ha <sup>-1</sup> (Z <sub>25.0</sub> S <sub>6.0</sub> )	6.33
S.Em.	0.67
C.D. ( $p \leq 0.05$ )	1.95

root rot of chickpea (Gaur and Vaidya 1983) and *Rhizoctonia bataticola* rot of groundnut (Murugesan and Mahadevan 1987). The cyclic incorporation of 1.5 and 6.0 t straw ha<sup>-1</sup> decreased the disease score significantly by 39.2 and 33.3 % in comparison to control, respectively. The residual effect of 6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 1.5 t straw ha<sup>-1</sup> decreased the disease score significantly by 52.9, 47.1 and 47.1 % in comparison to control, respectively. The residual effect of 6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 3.0 t straw ha<sup>-1</sup> decreased the disease score significantly by 49.1, 58.8 and 70.6 % in comparison to control, respectively. The residual effect of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 6.0 t straw ha<sup>-1</sup> decreased the diseases score significantly by 23.5 and 25.5 % over control, respectively. Thus, the residual effect of increasing rates of zinc sulphate application to I year rice crop in combination with the cyclic incorporation of cereal straw showed a significant reduction in the severity of brown spot disease in II year rice crop.

The disease score also had a significant effect on the grain yields of II rice crop; there was a significant inverse relationship ( $r = -0.619$ , significant at  $p \leq 0.05$ ) between the disease score and the grain yield of II rice crop (Fig. 3).

**Fig. 3** The relationship between the disease score of brown spot and II year rice grain yields in 2006–07. \*Significant at  $p \leq 0.05$ 

#### Zinc concentration in flag leaves of rice and wheat

In the I year (2005–2006), the application of 6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I rice crop increased the concentration of Zn in the flag leaves of rice crop significantly to 20.86, 21.27 and 25.12 mg Zn kg<sup>-1</sup> which were 18.3, 20.6 and 42.5 % higher over control (17.63 mg Zn kg<sup>-1</sup>), respectively (Table 2). Similar observations have been recorded earlier in rice (cv. IR-62) plants by Shah and De Datta (1991). Application of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I rice crop along with the incorporation of 1.5 t wheat straw ha<sup>-1</sup> increased the concentration of Zn in the flag leaves of I rice crop significantly to 21.82 and 25.29 mg kg<sup>-1</sup> which were 23.8 and 43.5 % higher over control, respectively. Application of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop along with the incorporation of 3.0 t wheat straw ha<sup>-1</sup> increased the concentration of Zn in the flag leaves of I rice crop significantly to 22.97 and 25.17 mg Zn kg<sup>-1</sup> which were 30.3 and 42.7 % higher over control, respectively. Application of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I rice crop in combination with the incorporation of 6.0 t wheat straw ha<sup>-1</sup> increased the concentration of Zn in the flag leaves of I rice crop significantly to 20.29 and 22.82 mg Zn kg<sup>-1</sup>, which were 15.1 and 29.4 % over control, respectively. Thus, the application of ZnSO<sub>4</sub> along with the incorporation of wheat straw at rates up to 3 t ha<sup>-1</sup> prior to transplanting of rice crop ensured a higher supply of Zn to rice plants.

However, no significant effect of different treatments was observed on the concentration of Zn in the flag leaves of I year (2005–2006) wheat crop.

In the second year (2006–2007), the residual effect of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop increased the Zn concentration in the flag leaves of II year rice crop significantly to 24.53 mg Zn kg<sup>-1</sup> which was 31.1 % higher over control (18.72 mg Zn kg<sup>-1</sup>). The residual

**Table 2** Effect of different levels of zinc sulphate applied to I year rice crop and cyclic incorporation of cereal straw on Zn concentrations (mg/kg dry matter) in flag leaves of rice and wheat

Treatments	2005–2006		2006–2007	
	Rice	Wheat	Rice	Wheat
Control ( $Z_0 S_0$ )	17.63	23.13	18.72	22.55
6.25 kg ZnSO <sub>4</sub> ha <sup>-1</sup> ( $Z_{6.25} S_0$ )	20.86	23.53	21.37	22.70
12.5 kg ZnSO <sub>4</sub> ha <sup>-1</sup> ( $Z_{12.5} S_0$ )	21.27	25.77	21.43	23.60
25.0 kg ZnSO <sub>4</sub> ha <sup>-1</sup> ( $Z_{25.0} S_0$ )	25.12	26.00	24.53	23.97
1.5 t straw ha <sup>-1</sup> ( $Z_0 S_{1.5}$ )	18.19	23.57	19.23	23.75
6.25 kg ZnSO <sub>4</sub> + 1.5 t straw ha <sup>-1</sup> ( $Z_{6.25} S_{1.5}$ )	18.18	23.63	21.27	24.03
12.5 kg ZnSO <sub>4</sub> + 1.5 t straw ha <sup>-1</sup> ( $Z_{12.5} S_{1.5}$ )	21.82	24.47	25.20	24.35
25.0 kg ZnSO <sub>4</sub> + 1.5 t straw ha <sup>-1</sup> ( $Z_{25.0} S_{1.5}$ )	25.29	24.90	30.35	31.60
3.0 t straw ha <sup>-1</sup> ( $Z_0 S_{3.0}$ )	15.95	23.30	16.30	25.50
6.25 kg ZnSO <sub>4</sub> + 3.0 t straw ha <sup>-1</sup> ( $Z_{6.25} S_{3.0}$ )	18.88	23.43	22.38	27.73
12.5 kg ZnSO <sub>4</sub> + 3.0 t straw ha <sup>-1</sup> ( $Z_{12.5} S_{3.0}$ )	22.97	24.30	22.94	28.35
25.0 kg ZnSO <sub>4</sub> + 3.0 t straw ha <sup>-1</sup> ( $Z_{25.0} S_{3.0}$ )	25.17	24.97	25.67	32.90
6.0 t straw ha <sup>-1</sup> ( $Z_0 S_{6.0}$ )	16.39	24.13	15.07	23.40
6.25 kg ZnSO <sub>4</sub> + 6.0 t straw ha <sup>-1</sup> ( $Z_{6.25} S_{6.0}$ )	19.12	24.20	19.13	26.77
12.5 kg ZnSO <sub>4</sub> + 6.0 t straw ha <sup>-1</sup> ( $Z_{12.5} S_{6.0}$ )	20.29	24.37	20.77	27.80
25.0 kg ZnSO <sub>4</sub> + 6.0 t straw ha <sup>-1</sup> ( $Z_{25.0} S_{6.0}$ )	22.82	25.37	21.40	32.67
S.Em.	0.90	1.14	1.22	1.88
C.D. ( $p \leq 0.05$ )	2.61	NS	3.53	5.42

effect of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 1.5 t straw ha<sup>-1</sup> increased the Zn concentration in the flag leaves of II year rice crop significantly to 25.20 and 30.35 mg Zn kg<sup>-1</sup> which were 34.6 and 62.1 % higher over control, respectively. The residual effect of 6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 3.0 t straw ha<sup>-1</sup> increased the Zn concentration in the flag leaves of II year rice crop significantly to 22.38, 22.94 and 25.67 mg Zn kg<sup>-1</sup> which were 19.6, 22.5 and 37.1 % higher over control, respectively. These observations supported the hypothesis that the cyclic incorporation of cereal straw led to a higher residual effect of ZnSO<sub>4</sub> applied to the previous year rice crop.

In the second year (2006–2007), an increment in the cyclic incorporation of straw (1.5–3.0 t ha<sup>-1</sup>) resulted in a significant increase in the Zn concentration of the flag leaves of II year wheat crop but at the highest rate of straw

incorporation (6.0 t ha<sup>-1</sup>), a reduction occurred in the Zn concentration of the flag leaves of wheat crop. The residual effect of the increasing rates of ZnSO<sub>4</sub> applied to I year rice crop in conjunction with the cyclic incorporation of straw helped in increasing the concentration of Zn in the flag leaves of II wheat crop. The residual effect of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 1.5 t straw ha<sup>-1</sup> increased the Zn concentration in the flag leaves of II year wheat crop significantly to 31.60 mg Zn kg<sup>-1</sup> which was 40.1 % higher over control (22.55 mg Zn kg<sup>-1</sup>). The residual effect 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 3.0 t straw ha<sup>-1</sup> increased the Zn concentration in the flag leaves of II wheat crop significantly to 28.35 and 32.90 mg Zn kg<sup>-1</sup> which were 25.7 and 45.9 % higher over control, respectively. The residual effect of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop along with the cyclic incorporation of 6.0 t straw ha<sup>-1</sup> increased the Zn concentration in the flag leaves of II wheat crop significantly to 32.67 mg Zn kg<sup>-1</sup> which was 44.9 % higher over control.

#### Zinc concentration in grains and straw of rice and wheat

In I year (2005–2006), the application of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the Zn concentration in the grains of I year rice crop significantly to 18.66 mg Zn kg<sup>-1</sup> which was 70.9 % higher over control (10.92 mg Zn kg<sup>-1</sup>) (Table 3). Incorporation of 1.5 t wheat straw ha<sup>-1</sup> along with the application of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the Zn concentration in the grains of I year rice crop significantly to 23.90 mg Zn kg<sup>-1</sup> which was 118.9 % higher over control. Incorporation of 3.0 t wheat straw ha<sup>-1</sup> along with the application of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the Zn concentration in the grains of I year rice crop significantly to 25.03 mg Zn kg<sup>-1</sup> which was 129.2 % higher over control. However, the incorporation of 6.0 t wheat straw ha<sup>-1</sup> along with the application of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop failed to increase the concentration of Zn in the grains of I year rice crop in comparison to control but it was significantly higher over the value (9.57 mg Zn kg<sup>-1</sup>) obtained with the incorporation of 6.0 t wheat straw ha<sup>-1</sup>. The incorporation of the lower and moderate levels of straw (1.5 and 3.0 t wheat straw ha<sup>-1</sup>) produced and released organic acids forming the soluble organo-zinc complexes which are more labile to ensure a higher supply of Zn to plants while the incorporation of further higher rate of straw (6 t ha<sup>-1</sup>) might have lowered the availability of Zn especially, at lower rates of ZnSO<sub>4</sub> application due to the microbial immobilization of Zn.



**Table 3** Effect of different levels of zinc sulphate applied to I year rice crop and cyclic incorporation of cereal straw on Zn concentrations ( $\text{mg kg}^{-1}$  dry matter) in grains and straw of rice and wheat

Treatments	Rice 2005–2006		Wheat 2005–2006		Rice 2006–2007		Wheat 2006–2007	
	Grains	Straw	Grains	Straw	Grains	Straw	Grains	Straw
Control ( $Z_0 S_0$ )	10.92	14.48	24.25	9.63	10.00	15.60	14.60	5.23
6.25 kg $\text{ZnSO}_4 \text{ ha}^{-1}$ ( $Z_{6.25} S_0$ )	14.83	17.53	25.07	10.87	13.53	16.93	15.80	6.43
12.5 kg $\text{ZnSO}_4 \text{ ha}^{-1}$ ( $Z_{12.5} S_0$ )	14.67	17.24	25.07	11.37	14.77	19.30	18.23	6.30
25.0 kg $\text{ZnSO}_4 \text{ ha}^{-1}$ ( $Z_{25.0} S_0$ )	18.66	21.82	26.90	11.63	14.87	19.70	18.87	8.23
1.5 t straw $\text{ha}^{-1}$ ( $Z_0 S_{1.5}$ )	13.70	14.74	26.20	9.97	11.30	15.73	13.80	4.75
6.25 kg $\text{ZnSO}_4 + 1.5$ t straw $\text{ha}^{-1}$ ( $Z_{6.25} S_{1.5}$ )	15.57	14.90	26.40	9.93	13.90	15.67	20.13	4.05
12.5 kg $\text{ZnSO}_4 + 1.5$ t straw $\text{ha}^{-1}$ ( $Z_{12.5} S_{1.5}$ )	16.18	18.40	27.00	10.83	14.30	22.20	21.80	4.15
25.0 kg $\text{ZnSO}_4 + 1.5$ t straw $\text{ha}^{-1}$ ( $Z_{25.0} S_{1.5}$ )	23.90	21.93	27.93	12.73	14.53	25.63	22.00	4.77
3.0 t straw $\text{ha}^{-1}$ ( $Z_0 S_{3.0}$ )	11.35	12.87	26.00	9.10	15.07	12.33	17.83	5.00
6.25 kg $\text{ZnSO}_4 + 3.0$ t straw $\text{ha}^{-1}$ ( $Z_{6.25} S_{3.0}$ )	14.70	15.53	25.40	10.60	15.73	13.47	18.70	5.03
12.5 kg $\text{ZnSO}_4 + 3.0$ t straw $\text{ha}^{-1}$ ( $Z_{12.5} S_{3.0}$ )	17.20	19.85	22.77	10.85	10.67	13.57	18.70	4.85
25.0 kg $\text{ZnSO}_4 + 3.0$ t straw $\text{ha}^{-1}$ ( $Z_{25.0} S_{3.0}$ )	25.03	21.95	23.10	10.87	10.97	14.87	19.10	6.57
6.0 t straw $\text{ha}^{-1}$ ( $Z_0 S_{6.0}$ )	9.57	12.81	25.40	9.55	9.90	15.47	15.80	5.17
6.25 kg $\text{ZnSO}_4 + 6.0$ t straw $\text{ha}^{-1}$ ( $Z_{6.25} S_{6.0}$ )	10.53	16.30	24.50	11.20	10.77	16.23	15.93	5.37
12.5 kg $\text{ZnSO}_4 + 6.0$ t straw $\text{ha}^{-1}$ ( $Z_{12.5} S_{6.0}$ )	12.37	15.31	28.10	11.70	12.87	19.17	16.50	6.10
25.0 kg $\text{ZnSO}_4 + 6.0$ t straw $\text{ha}^{-1}$ ( $Z_{25.0} S_{6.0}$ )	16.40	19.33	26.75	11.33	12.93	15.48	19.17	4.95
S.Em.	2.32	0.94	1.06	1.53	1.14	1.46	1.66	0.61
C.D. ( $p \leq 0.05$ )	6.70	2.71	3.06	NS	3.30	4.21	4.78	1.76

With regard to the concentration of Zn in the straw of I year rice, the application of 6.25, 12.50 and 25.00 kg  $\text{ZnSO}_4 \text{ ha}^{-1}$  to I year rice crop increased the Zn concentration in straw of I rice crop significantly to 17.53, 17.24 and 21.82 mg Zn  $\text{kg}^{-1}$  which were 21.1, 19.0 and 50.7 % higher over control (14.48 mg Zn  $\text{kg}^{-1}$ ), respectively. The incorporation of 1.5 t wheat straw  $\text{ha}^{-1}$  along with the application of 12.50 and 25.00 kg  $\text{ZnSO}_4 \text{ ha}^{-1}$  to I year rice crop increased the Zn concentration in the straw of I year rice crop significantly to 18.40 and 21.93 mg Zn  $\text{kg}^{-1}$  which were 27.1 and 51.5 % higher over control, respectively. The incorporation of 3.0 t wheat straw  $\text{ha}^{-1}$  in combination with the application of 12.50 and 25.00 kg  $\text{ZnSO}_4 \text{ ha}^{-1}$  to I year rice crop increased the Zn concentration in the straw of I year rice crop significantly to 19.85 and 21.95 mg Zn  $\text{kg}^{-1}$  which were 37.1 and 51.6 % higher over control, respectively. Incorporation of 6.0 t wheat straw  $\text{ha}^{-1}$  along with the application of 25.00 kg  $\text{ZnSO}_4 \text{ ha}^{-1}$  to I year rice crop increased the Zn concentration in the I year rice straw significantly to 19.33 mg Zn  $\text{kg}^{-1}$  which was only 33.5 % higher over control.

During I year (2005–2006), the residual effect of 25.00 kg  $\text{ZnSO}_4 \text{ ha}^{-1}$  applied to I year rice crop in combination with the cyclic incorporation of 1.5 t straw  $\text{ha}^{-1}$  increased the Zn concentration in grains of I year wheat significantly to 26.90 mg Zn  $\text{kg}^{-1}$  which was 15.2 % higher over control (24.25 mg Zn  $\text{kg}^{-1}$ ). The residual effect of 12.50 kg  $\text{ZnSO}_4 \text{ ha}^{-1}$  applied to I year rice crop in combination with the cyclic incorporation of 6.0 t straw  $\text{ha}^{-1}$  increased the Zn concentration in wheat grains significantly to 28.10 mg Zn  $\text{kg}^{-1}$  which was 15.9 % higher over control. An increase in the concentration of Zn in the wheat grains due to Zn application has been recorded earlier by Bharadwaj and Prasad (1981) and Prasad et al. (1981). However, no significant effect of any treatment was observed on the Zn content of I year wheat straw.

In II year (2006–2007), the residual effect of 6.25, 12.50 and 25.00 kg  $\text{ZnSO}_4 \text{ ha}^{-1}$  applied to I year rice crop increased the Zn concentration in the grains of II year rice crop significantly to 13.53, 14.77 and 14.87 mg Zn  $\text{kg}^{-1}$  which were 35.3, 47.7 and 48.7 % higher over control (10.00 mg Zn  $\text{kg}^{-1}$ ), respectively. The residual effect of

6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 1.5 t straw ha<sup>-1</sup> increased the concentration of Zn in the grains of II year rice crop significantly to 13.90, 14.30 and 14.53 mg Zn kg<sup>-1</sup> which were 39.0, 43.0 and 45.3 % higher over control, respectively. The cyclic incorporation of 3.0 t straw ha<sup>-1</sup> alone and in conjunction with the residual effect of 6.25 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop increased the concentration of Zn in the grains of II year rice crop significantly to 15.07 and 15.73 mg Zn kg<sup>-1</sup> which were 50.7 and 57.3 % higher over control, respectively.

In II year (2006–2007), the residual effect of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 1.5 t wheat straw ha<sup>-1</sup> increased the Zn concentration in the straw of II year rice crop significantly to 22.20 and 25.63 mg Zn kg<sup>-1</sup> which were 42.3 and 64.3 % higher over control (15.60 mg Zn kg<sup>-1</sup>), respectively.

In II year (2006–2007), the residual effect of 6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 1.5 t straw ha<sup>-1</sup> increased the Zn concentration in the grains of II year wheat crop significantly to 20.13, 21.80 and 22.00 mg Zn kg<sup>-1</sup> which were 37.9, 49.3 and 50.7 % higher over control (14.60 mg Zn kg<sup>-1</sup>), respectively. The cyclic incorporation of only 3.0 and 6.0 t straw ha<sup>-1</sup> resulted in a reduction in the concentration of Zn in the wheat grains; however, the magnitude of reduction was statistically non-significant. Similar results have been reported by Narendra et al. (1988).

In II year, the residual effect of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop increased the Zn concentration in the straw of II year wheat crop significantly to 8.23 mg Zn kg<sup>-1</sup> which was 57.4 % higher over control (5.23 mg Zn

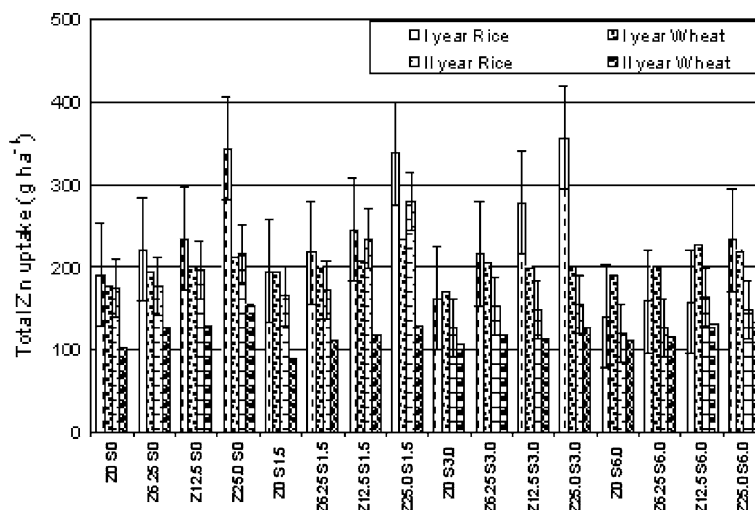
kg<sup>-1</sup>). Similar increase has been reported earlier by Khamparia et al. (1994).

#### Total zinc uptake by rice and wheat

The data on the effect of Zn applied to I year rice crop and the cyclic incorporation of straw on the total Zn uptake by rice and wheat crops during I and II year are presented in Fig. 4. In I year, the application of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the total Zn uptake of I year rice crop significantly by 79.8 % over control. Incorporation of 1.5 t wheat straw ha<sup>-1</sup> along with the application of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the total Zn uptake of I year rice crop significantly by 76.9 % over control. Incorporation of 3.0 t wheat straw ha<sup>-1</sup> along with the application of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the total Zn uptake of I year rice crop significantly by 45.5 and 86.9 % over control, respectively.

In II year, the residual effect of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop increased the total Zn uptake of II year rice crop significantly by 23.9 % over control. The residual effect of 12.50 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 1.5 t straw ha<sup>-1</sup> increased the total Zn uptake of II year rice crop significantly by 34.8 % over control. The residual effect of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 1.5 t straw ha<sup>-1</sup> increased the total Zn uptake of II year rice crop significantly by 60.2 % over control. The cyclic incorporation of 3.0 and 6.0 t straw ha<sup>-1</sup> without any application of ZnSO<sub>4</sub> to I year rice crop decreased the total Zn uptake of II year rice crop significantly by 27.5 and 30.6 % in comparison to control, respectively. The residual effect of lower level of ZnSO<sub>4</sub> (6.25 kg ZnSO<sub>4</sub> ha<sup>-1</sup>) applied to I year rice crop in combination with the cyclic incorporation

**Fig. 4** Effect of different levels of zinc sulphate applied to I year rice crop and cyclic incorporation of cereal straw on total Zn uptake of rice and wheat crops in 2005–2006 and 2006–2007. Vertical bars C.D. at  $p \leq 0.05$



of 6.0 t straw ha<sup>-1</sup> also decreased the total uptake of Zn by II year rice crop significantly by 27.1 % in comparison to control.

No significant effect of different treatments was noted on the total Zn uptake of I and II year wheat crop.

#### Total zinc uptake by rice–wheat rotation

The data pertaining to the effect of ZnSO<sub>4</sub> applied to I year rice crop and the cyclic incorporation of straw on the total Zn uptake by rice–wheat rotation are presented in Fig. 5. The application of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the total Zn uptake of I year rice–wheat rotation significantly by 18.3 and 51.1 % over control, respectively. The cyclic incorporation of 1.5 t straw/ha along with the application of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the total Zn uptake by I year rice–wheat rotation significantly by 23.4 and 55.4 % over control, respectively. The cyclic incorporation of 3.0 t wheat straw ha<sup>-1</sup> in combination with the application of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the total Zn uptake by I year rice–wheat rotation significantly by 29.9 and 51.8 % over control, respectively. The cyclic incorporation of 6.0 t wheat straw ha<sup>-1</sup> in combination with the application of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the total Zn uptake of I year rice–wheat rotation significantly by only 23.2 % over control.

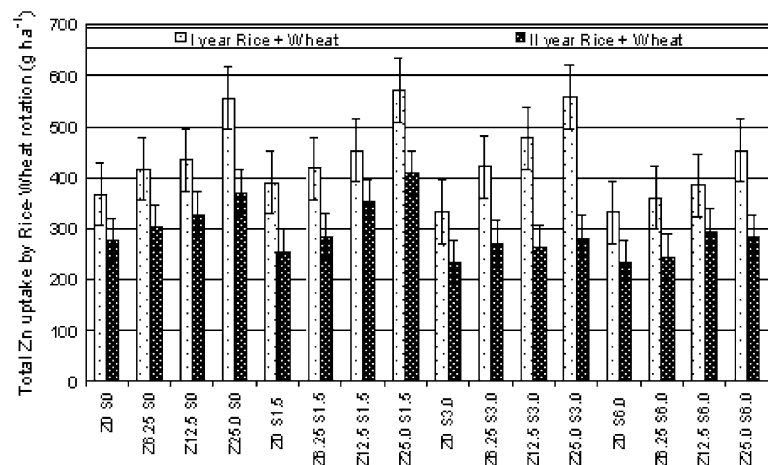
During II year (2006–2007), the residual effect of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop increased the total uptake of II year rice–wheat rotation significantly by 18.0 and 33.6 % over control, respectively. The residual effect of 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 1.5 t straw ha<sup>-1</sup> increased the total Zn uptake of II year rice–wheat rotation significantly by 27.5 and 47.6 % over control, respectively. Thus, the cyclic

incorporation 1.5 t straw ha<sup>-1</sup> assisted in improving the residual effect of ZnSO<sub>4</sub> applied to I year rice crop on the total Zn removal by the subsequent year rice–wheat rotation.

#### DTPA-extractable zinc in soil

The data on the effect of ZnSO<sub>4</sub> applied to I year rice crop and the cyclic incorporation of straw on the DTPA-extractable soil Zn after harvest of the wheat crop during 2005–2006 and 2006–2007 are given in Table 4. After the harvest of I year wheat crop, the DTPA-extractable Zn in soil showed an increasing trend with the increasing rate of ZnSO<sub>4</sub> applied to I year rice crop. Application of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased the DTPA-extractable soil Zn significantly to 0.83 mg Zn kg<sup>-1</sup> soil which was 143.5 % over control (0.34 mg Zn kg<sup>-1</sup> soil). As regards the effect of cyclic incorporation of cereal straw on the DTPA-extractable Zn in the soil, the data clearly indicated that an increment in the rate of straw incorporation from 1.5 to 6.0 t ha<sup>-1</sup> alone or in combination of lower rates of Zn fertilizer (6.25 and 12.50 kg ZnSO<sub>4</sub> ha<sup>-1</sup>) failed to increase the content of DTPA-extractable Zn in soil in comparison to control possibly due to the immobilization of Zn by the microbes during the decomposition of the cereal straw. The residual effect of 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of cereal straw at 1.5, 3.0 and 6.0 t ha<sup>-1</sup> increased the content of DTPA-extractable soil Zn in soil significantly to 0.94, 1.03 and 0.65 mg Zn kg<sup>-1</sup> which were 175.5, 202.4 and 92.0 % higher over control, respectively. This indicated that the cyclic incorporation of low and moderate quantity of crop residues had a favorable effect on the bioavailability of ZnSO<sub>4</sub> applied to the previous rice crop. Duraisamy et al. (1988) also reported that the application of zinc (10–20 mg kg<sup>-1</sup> soils) to rice crop improved the availability of zinc in soil.

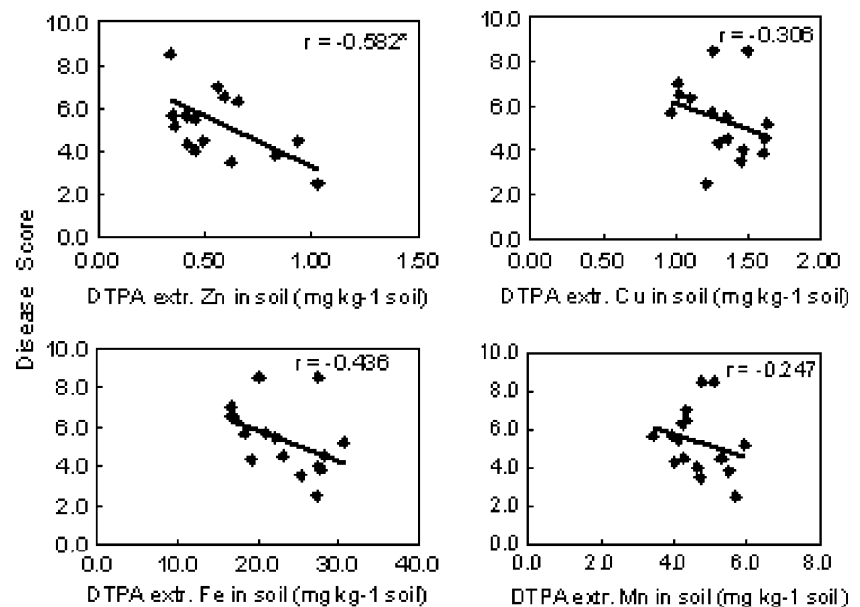
**Fig. 5** Effect of different levels of zinc sulphate applied to I year rice crop and cyclic incorporation of cereal straw on total Zn uptake of rice–wheat rotation in 2005–2006 and 2006–2007. Vertical bars C.D. at  $p \leq 0.05$



**Table 4** Effect of different levels of zinc sulphate applied to I year rice crop and cyclic incorporation of cereal straw on the DTPA-extractable Zn in soil after the harvest of wheat crop in 2005–2006 and 2006–2007

Treatments	DTPA-extractable Zn (mg kg <sup>-1</sup> soil)	
	2005–2006 After I year wheat crop	2006–2007 After II year wheat crop
Control (Z <sub>0</sub> S <sub>0</sub> )	0.34	0.44
6.25 kg ZnSO <sub>4</sub> ha <sup>-1</sup> (Z <sub>6.25</sub> S <sub>0</sub> )	0.35	0.64
12.5 kg ZnSO <sub>4</sub> ha <sup>-1</sup> (Z <sub>12.5</sub> S <sub>0</sub> )	0.46	0.91
25.0 kg ZnSO <sub>4</sub> ha <sup>-1</sup> (Z <sub>25.0</sub> S <sub>0</sub> )	0.83	1.22
1.5 t straw ha <sup>-1</sup> (Z <sub>0</sub> S <sub>1.5</sub> )	0.36	0.64
6.25 kg ZnSO <sub>4</sub> + 1.5 t straw ha <sup>-1</sup> (Z <sub>6.25</sub> S <sub>1.5</sub> )	0.45	0.83
12.5 kg ZnSO <sub>4</sub> + 1.5 t straw ha <sup>-1</sup> (Z <sub>12.5</sub> S <sub>1.5</sub> )	0.49	1.11
25.0 kg ZnSO <sub>4</sub> + 1.5 t straw ha <sup>-1</sup> (Z <sub>25.0</sub> S <sub>1.5</sub> )	0.94	1.14
3.0 t straw ha <sup>-1</sup> (Z <sub>0</sub> S <sub>3.0</sub> )	0.34	0.67
6.25 kg ZnSO <sub>4</sub> + 3.0 t straw ha <sup>-1</sup> (Z <sub>6.25</sub> S <sub>3.0</sub> )	0.42	0.73
12.5 kg ZnSO <sub>4</sub> + 3.0 t straw ha <sup>-1</sup> (Z <sub>12.5</sub> S <sub>3.0</sub> )	0.62	1.23
25.0 kg ZnSO <sub>4</sub> + 3.0 t straw ha <sup>-1</sup> (Z <sub>25.0</sub> S <sub>3.0</sub> )	1.03	1.46
6.0 t straw ha <sup>-1</sup> (Z <sub>0</sub> S <sub>6.0</sub> )	0.41	0.88
6.25 kg ZnSO <sub>4</sub> + 6.0 t straw ha <sup>-1</sup> (Z <sub>6.25</sub> S <sub>6.0</sub> )	0.56	0.92
12.5 kg ZnSO <sub>4</sub> + 6.0 t straw ha <sup>-1</sup> (Z <sub>12.5</sub> S <sub>6.0</sub> )	0.59	1.07
25.0 kg ZnSO <sub>4</sub> + 6.0 t straw ha <sup>-1</sup> (Z <sub>25.0</sub> S <sub>6.0</sub> )	0.65	1.03
S.Em.	0.10	0.05
C.D. ( <i>p</i> ≤ 0.05)	0.30	0.13

**Fig. 6** The relationship between disease score of brown spot in rice and DTPA extr. micronutrient cations in soil after the harvest of I year wheat crop. \*Significant at *p* ≤ 0.05



After the harvest of II year (2006–2007) wheat crop, the DTPA-extractable soil Zn under the treatments receiving 6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop increased significantly to 0.64, 0.91 and 1.22 mg Zn kg<sup>-1</sup> soil which were 45.7, 107.1 and 177.8 % higher over control (0.44 mg Zn kg<sup>-1</sup> soil), respectively. The cyclic incorporation of 1.5, 3.0 and 6.0 t straw ha<sup>-1</sup> with no

application of ZnSO<sub>4</sub> to I year rice crop increased the DTPA-extractable soil Zn after II year wheat significantly to 0.64, 0.67 and 0.88 mg Zn kg<sup>-1</sup> soil which were 44.5, 52.1 and 99.5 % higher over control, respectively. The residual effect of 6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 1.5 t straw ha<sup>-1</sup> increased the DTPA-



extractable soil Zn significantly to 0.83, 1.11 and 1.14 mg Zn kg<sup>-1</sup> soil which were 89.5, 151.7 and 158.8 % higher over control, respectively. The residual effect of 6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 3.0 t straw ha<sup>-1</sup> increased the DTPA-extractable soil Zn after II year wheat significantly to 0.73, 1.23 and 1.46 mg Zn kg<sup>-1</sup> soil which were 66.4, 180.2 and 232.3 % higher over control, respectively. The residual effect of 6.25, 12.50 and 25.00 kg ZnSO<sub>4</sub> ha<sup>-1</sup> applied to I year rice crop in combination with the cyclic incorporation of 6.0 t straw ha<sup>-1</sup> increased the DTPA-extractable soil Zn significantly to 0.92, 1.07 and 1.03 mg Zn kg<sup>-1</sup> soil which were 108.9, 143.6 and 134.5 % higher over control, respectively.

In order to test the hypothesis that whether there was any relationship between the content of DTPA-extractable micronutrient cations in soil and the severity of brown spot disease of rice, the contents of DTPA-extractable micronutrients (Zn, Cu, Fe and Mn) in soil after the harvest of I year wheat crop (2005–2006) were correlated with the score of brown spot disease for the II year (2006–2007) rice crop. A significant inverse relationship ( $r = -0.582$ , significant at  $p \leq 0.05$ ) was noted between the DTPA-extractable Zn content of soil and disease score (Fig. 6). The observed inverse relationship between DTPA-extractable Zn and the disease score could be related to the importance of Zn in maintaining the integrity or stability of biological membranes (Bettger and O'Dell 1981) which makes the Zn-deficient plants more susceptible to plant diseases.

## Conclusions

Under rice–wheat rotation, the application of 25.0 kg ZnSO<sub>4</sub> ha<sup>-1</sup> to I year rice crop along with the cyclic incorporation of 1.5 t cereal straw ha<sup>-1</sup> gives higher grain yields, Zn concentration in plant tissues and total Zn uptake by crops. The practice ensures a higher availability of ZnSO<sub>4</sub> applied to the I rice crop as well as to the subsequently grown crops. In the event of the outbreak of brown spot disease of rice, serious yield damage could be afflicted to the crop growing on Zn-deficient soils.

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**Conflict of interest** The authors declare that they have no competing interests.

**Author contribution** The work is part of the Ph.D. thesis of RD who performed field and laboratory tasks and drafted the manuscript. PCS designed the experiment, supervised the work and participated in

the chemical analysis of the soil and plant samples and correction of the manuscript. Both authors read and approved the final manuscript.

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## References

- Agrawal SK, Bhan S (1997) Effect of levels of zinc sulphate application on yield and net return in rice-wheat cropping sequence. *Indian J Agric Res* 31:174–178
- Bettger WJ, O'Dell BL (1981) A critical physiological role of zinc in the structure and function of biomembranes. *Life Sci* 28:1425–1438
- Bharadwaj SP, Prasad SN (1981) Response of rice-wheat to zinc under irrigated condition in Doon valley. *J Indian Soc Soil Sci* 29:220–224
- Channabasavanna AS, Yelamali SG, Biradar DP (2001) Response of rice sources of organic manures and levels of zinc sulphate in deep black soils. *Indian J Agron* 46:458–461
- Duraisamy P, Kothandaramam GV, Chellamuthu S (1988) Effect of amendments and zinc on the availability, content and uptake of zinc and iron by rice Bhavani in sodic soil. *Madras Agric J* 75:119–124
- Gaur RB, Vaidya PK (1983) Reduction of root rot of chickpea by soil application of phosphorus and zinc. *Int Chickpea News* 1(9):17–18
- Hanafi EM, El Khadrawy HH, Ahmed WM, Zaabal MM (2012) Some observations on rice straw with emphasis on updates of its management. *World Appl Sci J* 16:354–361
- International Rice Research Institute (1996) Standard evaluation system for rice. International Rice Research Institute, Manila
- Khamparia RS, Sharma BL, Rathore GS (1994) Suitability of soil test methods and response in wheat to zinc in some alfisols and vertisols. *J Indian Soc Soil Sci* 42:88–92
- Lindsay WL, Norvell WA (1978) Development of soil test for zinc, iron, manganese and copper. *Soil Sci Soc Am J* 42:421–428
- Meelu OP, Morris RA (1988) Green manure management in rice-based cropping system. In: Pollard ML (ed) Green manure in rice farming: Proceeding of a symposium on sustainable agriculture, the role of green manure crops in rice farming systems, Manila, 25–29 May 1987. International Rice Research Institute, Los Banos, pp 209–222
- Murugesan K, Mahadevan A (1987) Control of *Rhizoctonia bataticola* of groundnut by trace elements. *Int J Trop Plant Dis* 5:43–57
- Nambiar KKM (1992) Annual Report (1987–1988 and 1988–1989) of all India Coordinated Project on Long Term Fertilizer Experiments (Indian Council of Agricultural Research). Indian Agricultural Research Institute, New Delhi
- Page AL, Miller RH, Keeney DR (eds) (1982) Methods of Soil Analysis. Part 1 and 2, ASA Inc. & SSSA Inc., Madison
- Powlson DS (1994) Quantification of nutrient cycles using long-term experiments. In: Leigh RA, Johnston AE (eds) Long-term experiments in agricultural and ecological sciences. CAB International, Wallingford, pp 97–115
- Prasad K, Singh BP, Singh RB (1981) Response of wheat varieties to soil applied zinc. *J Indian Soc Soil Sci* 29:400–401
- Prasad RA, Singh RK, Rani A, Singh DK (2000) Partial factor productivity of N and its use efficiency in rice and wheat. *Fert News* 45:63–65



- Sakal R, Singh AP, Singh BP (1985) A comparative study of direct and residual effect of zinc carriers on the response of crops in calcareous soil. *J Indian Soc Soil Sci* 33:836–840
- Saravanan A, Ramnathan KM (1988) Effect of zinc application on its availability and yield on rice. *Oryza* 25:271–273
- Shah AL, De Datta SK (1991) Sulphur and zinc interactions in lowland rice. *Philipp J Crop Sci* 16:15–18
- Singh JP, Karamanos RE, Lewis NG, Stewart JWB (1986) Effectiveness of zinc fertilizer sources on nutrition of beans. *Can J Soil Sci* 66:183–187
- Singh N, Mehta SS, Singh B, Singh N, Singh B (1988) Varietal response of wheat to zinc. *Haryana J Agron* 2:133–134
- Snedecor GW, Cochran WG (1967) *Statistical methods*. Oxford and IBH Publishing Co., Calcutta
- Srivastava PC, Singh AP, Kumar S, Ramachandran V, Shrivastava M, D'souza SF (2008) Desorption and transformation of zinc in a mollisol and its uptake by plants in a rice-wheat rotation fertilized with either zinc-enriched biosludge from molasses or with inorganic zinc. *Biol Fertil Soils* 44:1035–1041
- Tisdale SL, Nelson WL, Beaton JD, Havlin JL (1997) *Soil fertility and fertilizer*, 5th edn. Prentice hall, New Delhi

