Rice Response to Granular Zinc Sources Varying in Water-Soluble Zinc

Nathan A. Slaton,* Edward E. Gbur, Jr., Charles E. Wilson, Jr., and Richard J. Norman

ABSTRACT

Water-soluble Zn (WsZn) levels in granular Zn fertilizers are reported to be a reliable estimate of fertilizer Zn availability to crops. Our objectives were to evaluate the immediate and residual effects of four commercial Zn fertilizers with WsZn ranging from 14 to 98% on the growth, Zn nutrition, and yield of field-grown flood-irrigated rice (*Oryza sativa* L.). Mehlich-3 extractable Zn response to Zn fertilization was also evaluated. Zinc fertilizers were applied at rates ranging from 2.3 to 18.0 kg Zn ha^{-1} at two locations in 2000. The immediate and residual effects of Zn fertilizer treatments on rice growth were measured in 2000 and 2001, respectively. Dry matter, tissue Zn concentration, and grain yield were increased from application of 13.5 kg Zn ha^{-1} for both sites during both years, but the magnitude of response varied between locations. During the first year, at both locations, whole-seedling Zn concentrations increased linearly as Zn rate increased and was affected by Zn source. Tissue Zn concentration generally declined as the fertilizer WsZn level declined. Zinc rate had the greatest influence on grain yields with near maximum yield produced when >9 kg Zn ha^{-1} was applied. During the second year, tissue Zn concentration and yield increased linearly or nonlinearly, depending on location, as Zn rate increased and were not affected by Zn source. During the first year, Zn source and rate influenced early season growth and Zn concentrations, but grain yield, Mehlich-3 soil Zn, and the residual benefits of Zn fertilization were affected only by application rate.

Zinc fertilizers are manufactured and sold in a variety of formulations (i.e., powders, granules, and liquids) with various chemical compositions and physical properties by numerous companies. One of the most controversial issues regarding granular Zn fertilizers is their ability to provide Zn to growing crops based on the level of water-soluble Zn. Commercially available granular Zn fertilizer sources contain a wide range of total Zn contents and levels of WsZn. Horstmeier (1998) reported that the WsZn content of commercially available Zn fertilizers submitted by growers ranged from 1 to 100%. The level of WsZn present in granular Zn fertilizers is reported to be a reliable estimate of the availability of fertilizer Zn to corn (*Zea mays* L.; Amrani et al., 1999; Giordano and Mortvedt, 1969; Mortvedt, 1992) and rice (Liscano et al., 2000). In general, plant uptake of fertilizer Zn decreases as the level of WsZn in fertilizer decreases. Nearly all of the published research suggests that Zn fertilizers should contain a minimum of 40 to 50% WsZn.

Several studies have examined crop response to Zn fertilizers varying in WsZn, but most have been conducted in the greenhouse to examine Zn uptake during vegetative plant growth (Amrani et al., 1999; Gangloff et al., 2002; Giordano and Mortvedt, 1969; Liscano et al., 2000; Mortvedt, 1992). Although these studies provide valid relationships regarding the relative availability of fertilizer Zn, some Zn fertilizer manufacturers have questioned the legitimacy of these studies since they were not conducted under field conditions and provide no information on crop grain yield. Critics also argue that fertilizers with low levels of WsZn slowly release Zn, which continuously supplies Zn to crops throughout the growing season, whereas Zn from fertilizers with high levels of WsZn is rapidly converted to less soluble and plant-available soil forms shortly after application (Boawn et al., 1957). Although these may be legitimate arguments, most Zn deficiencies occur during the seedling stages of plant development when plants have small root systems and may be subjected to adverse environmental conditions, which limit growth and nutrient uptake. Fertilizer physical properties (i.e., granule size) also influence fertilizer distribution and rate of granule dissolution, which may interact with fertilizer chemical properties to influence plant uptake of fertilizer nutrients (Liscano et al., 2000; Mortvedt, 1991).

Evaluation of the Zn nutritional status of seedling crops in response to Zn fertilization rate, source, or both appears to be an appropriate measure of the agronomic effectiveness of Zn fertilizers. The nutritional status of crops at specific, important growth stages is used to diagnose nutrient deficiencies and make fertilizer recommendations in nutrient monitoring programs on the premise that yield and nutrient status are related. For example, Carsky and Reid (1990) showed the Zn concentration of whole young corn plants was significantly correlated with relative corn yield.

The primary objectives of this study were to evaluate the immediate and residual effects of four Zn fertilizers differing in WsZn on the growth, Zn nutrition, and yield response of field-grown flood-irrigated rice. A secondary objective was to evaluate the short-term response of Mehlich-3 extractable soil Zn to Zn source and application rate. Our hypothesis was that Zn uptake and grain yield of rice, as well as Mehlich-3 extractable Zn would decrease as the WsZn of the selected Zn fertilizer sources decreased.

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Abbreviations: AOAC, Association of Official Analytical Chemists; DAF, days after flooding; ICAP, inductively coupled argon plasma spectroscopy; PTBS, Pine Tree Branch Station; RREC, Rice Research Extension Center; WsZn, water-soluble Zn; ZnLig10, Zn lignosulfonate 10% Zn; ZnOxy20, Zn oxysulfate 20% Zn; ZnOxy36, Zn Oxysulfate 36% Zn; ZnSul31, Zn Sulfate 31% Zn.

Table 1. Selected soil chemical properties of Zn fertilizer studies conducted at the Pine Tree Branch Experimental Station (PTBS) and the Rice Research Extension Center (RREC) during 2001.

		Mehlich-3 extractable nutrients									
Year-location	**Soil pH**	**P**	**K**	**Ca**	**Mg**	**Na**	**S**	**Fe**	**Mn**	**Zn**	**Cu**
		mg kg^{-1}									
2000-PTBS†	7.4	16	95	1805	312	56	4	178	105	1.2	1.4
2000-RREC‡	7.4	19	120	1865	148	75	18	138	300	1.2	1.5
2001-PTBS§	7.5	38	116	1871	296	73	22	234	72	2.1	0.9
2001-RREC§	7.4	45	108	1765	144	81	23	224	100	1.3	1.0

† Values are the mean of four individual composite samples taken from the untreated check in each replication before Zn fertilizer application.

‡ Values are the mean of 10 individual composite samples randomly taken from different plots in all four replications before Zn fertilizer application.

§ Soil test information is the average of samples taken from the four unfertilized control plots before flooding during 2001.

MATERIALS AND METHODS

Field studies were established at the Rice Research and Extension Center (RREC, 34.30°N lat.) near Stuttgart, AR and the Pine Tree Branch Station (PTBS, 35.08°N lat.) near Colt, AR during 2000 to evaluate rice response to Zn fertilizer source and rate of application. The soil at the RREC was a Dewitt silt loam (fine, smectitic, thermic, Typic Albaqualf) with an initial soil water pH of 5.8 and the soil at the PTBS was a Calhoun silt loam (fine-silty, mixed, active, thermic Typic Glossaqualfs) with an initial soil water pH of 7.0. At the RREC, 8960 kg lime ($CaCO_3$, calcium carbonate equivalent 90%) ha^{-1} was applied during February 2000 to increase soil pH and increase the likelihood of obtaining a plant response to Zn fertilization. At the PTBS, 2240 kg lime ($CaCO_3$) ha^{-1} was applied and incorporated immediately before establishing the plots in April 2000 for the same reason. The PTBS site received less lime because the soil initially had higher soil Ca, Mg, and pH than the Dewitt soil at the RREC due to the use of groundwater high in Ca and Mg bicarbonates for crop irrigation. Reservoir water, which has lower Ca, Mg, and HCO_3 concentrations, and is considered of higher quality, was used to irrigate rice at the RREC.

Before Zn application, composite soil samples were taken from four individual plots at the PTBS and 10 individual plots at the RREC to characterize the initial soil chemical properties at each site (Table 1). Soil samples were extracted with Mehlich-3 solution (Mehlich, 1984) and the elemental composition of the extracts was determined using inductively coupled argon plasma spectroscopy (ICAP). Soil pH was determined in a 1:2 soil water suspension with a glass electrode. Selected soil chemical properties from each location are listed in Table 1. Split applications of 68 kg P ha^{-1} (triple super phosphate) were made before seeding and again before establishment of the permanent flood to enhance the likelihood of Zn deficiency at both locations. Both sites also received 50 kg K ha^{-1} (muriate of potash).

Description of Zinc Fertilizers

Four Zn fertilizer sources including a $ZnSO_4$ (ZnSul31, 310 g Zn kg^{-1}, Tetra Micronutrients, The Woodlands, TX), Zn lignosulfonate (ZnLig10, 100 g Zn kg^{-1}, RSA MicroTech, LLC, Marysville, WA), and two Zn oxy-sulfate Zn sources (ZnOxy20, 200 g Zn kg^{-1}; and ZnOxy36, 360 g Zn kg^{-1}; Frit Industries, Inc., Ozark, AL) were selected for the study because they contained different WsZn contents (Table 2) and were the predominate commercially available Zn fertilizers sold in eastern Arkansas when this study was initiated. Bags of each Zn source were obtained from fertilizer dealers in Arkansas. Water-soluble and total Zn in each fertilizer were determined on duplicate samples of each source using Association of Official Analytical Chemists (AOAC) official methods 965.09 and 957.02, respectively (AOAC, 1990).

Subsamples of each fertilizer were passed through a nest of sieves to determine the particle-size distribution of each source (Table 2). Fertilizer granules representing the predominate granule size or sizes for each product were used for field application. Specifically, granules retained on the 1.0-mm sieve were used for ZnSul31, 2.0- and 3.4-mm sieve were used for ZnLig10, 2.0-mm sieve were used for ZnOxy20, and 1.0- and 2.0-mm sieve were used for ZnOxy36. Fertilizer granules retained on each sieve size were used to determine the average weight of 100 fertilizer granules. The average number of granules per unit area was determined for each product and application rate from data shown in Table 2. The average number of fertilizer granules m^{-2} kg^{-1} Zn was 81 for ZnSul31, 61 for ZnLig10, 29 for ZnOxy36, and 18 for ZnOxy20.

Zinc Fertilizer Treatments

Each Zn source was broadcast at rates of 2.3, 4.5, 9.0, 13.5, and 18.0 kg Zn ha^{-1} on 8.8-m^2 areas representing each individual plot. The Zn fertilizers were mechanically incorporated in the top 5 cm of soil. ‘Wells’ rice was seeded at 110 kg ha^{-1} immediately after the fertilizer was incorporated at the PTBS on 7 Apr. 2000 and at the RREC on 20 Apr. 2000. Each individual plot consisted of nine 4.9-m long rows with 18-cm wide row spacings. Rice emerged on 22 Apr. 2000 at the PTBS and 1 May 2000 at the RREC. For both studies, N was applied as urea to a dry soil surface at the rate of 135 kg N ha^{-1} before flooding at the 3- to 4-leaf growth stage. Nitrogen fertilizer

Table 2. Selected physical and chemical properties of four Zn fertilizers applied to the soil in field studies conducted during 2000.

				Particle-size distribution (sieve diameter, mm)‡				100 Granule weight (by sieve size)§		
Zn source	**Zn chemistry**	**Total Zn†**	**Water soluble Zn**	**3.35**	**2.00**	**1.00**	**<0.60**	**3.35**	**2.00**	**1.00**
		%	g kg^{-1}	% distribution by wt				g 100 fertilizer $granules^{-1}$		
ZnSul31	**Sulfate**	31	980	0.1	1.2	80.4	18.3	6.6	2.0	0.4
ZnLig10	**Lignosulfonate**	10	810	61.0	29.9	8.4	0.7	2.4	1.0	0.6
ZnOxy20	**Oxysulfate**	20	410	2.1	87.2	10.2	0.5	6.8	2.8	1.0
ZnOxy36	**Oxysulfate**	36	140	0.8	40.5	35.6	23.2	5.2	2.2	0.6

† Total Zn as indicated by the labeled guaranteed fertilizer analysis.

‡ Sieve sizes used were 6 (3.35 mm), 10 (2.00 mm), 18 (1.00 mm), and 30 (0.60 mm). Values indicate the percentage by weight of each fertilizer retained on selected sieve sizes.

§ The average weight of three replicates.

was applied and the flood established on 12 May at the PTBS and 18 May at the RREC. Crop management practices with respect to irrigation and pest control were similar to guidelines recommended by the Cooperative Extension Service for the dry-seeded, delayed-flood rice cultural system (Slaton, 2001).

At the PTBS, whole-plant samples were collected to measure aboveground dry matter accumulation 11 d after flooding (DAF, midtillering stage) by removing all of the aboveground plant tissue from a 0.9-m section from the first inside row. Plant samples were taken in a similar manner 12 DAF at the RREC. Plant samples were sequentially washed in deionized water and 0.1 *M* HCl, and rinsed in deionized water before drying to remove possible sources of Zn contamination. Samples were dried at 60°C to a constant weight, weighed, and ground in a Wiley mill to pass a 1-mm sieve. Ground tissue (0.5-g subsample) was digested with concentrated HNO_3 and 30% (w/w) H_2O_2 for determination of whole plant elemental composition (Jones and Case, 1990). Elemental analysis of plant digests was performed by ICAP. At maturity, a 2.8-m^2 area from the center four rows of each plot was harvested for grain yield with a small plot combine. Grain yields were adjusted to 120 g kg^{-1} moisture for statistical analysis.

Residual Effect of Zinc Fertilization

Plot boundaries were preserved at each location and a second rice crop was established in the spring of 2001 to evaluate the residual availability of the Zn fertilizer sources and rates of application to the second rice crop. Immediately before seeding, the soil, with the previous years rice stubble, was tilled to a depth of about 7.5 cm using a 1.5-m wide roto-tiller. Wells rice was seeded at a rate of 120 kg ha^{-1} on 10 Apr. 2001 at the PTBS and on 1 May 2001 at the RREC. Phosphorus (75 kg P ha^{-1} as triple super phosphate) and K (50 kg K ha^{-1} as muriate of potash) fertilizers were broadcast applied across all treatments to the soil surface after seeding.

To evaluate the influence of Zn source and application rate on Mehlich-3 extractable Zn 1 yr after Zn application, a composite soil sample, consisting of eight, 2-cm diameter cores taken to a depth of 10 cm, was collected from the middle of each individual plot after rice emergence in 2001. Soil was oven-dried, crushed, passed through a 2-mm sieve, and extracted with Mehlich-3 solution to determine plant-available soil nutrients, including Zn (Mehlich, 1984). Soil chemical properties were determined as previously described. The average Mehlich-3 extractable soil Zn concentrations from the unfertilized control plots before flooding in 2001 are listed in Table 1.

At the 4-leaf stage, 145 kg N ha^{-1} as urea was uniformly broadcast to the soil surface and a 10-cm deep flood was established and maintained until maturity when it was drained for harvest. At 12 to 14 DAF, plant samples were taken and processed as previously described to measure aboveground dry matter accumulation and tissue Zn concentration. At maturity, a 2.8-m^2 area from the middle four rows of each plot was harvested with a small plot combine for grain yield. Grain moisture was adjusted to a uniform moisture content of 120 g kg^{-1} for yield comparisons.

Statistical Analysis

At each location the experiment was arranged in a randomized complete block, 4 (Zn sources) × 5 (Zn application rates) factorial design plus an unfertilized control. Each treatment was replicated four times. Data were analyzed separately for each site-year combination. To characterize rice response to Zn fertilization, the unfertilized control means were compared with the 13.5 kg Zn ha^{-1} means, averaged across all four Zn sources, using single degree-of-freedom contrasts. The 13.5 kg Zn ha^{-1} rate was used because it closely approximates the recommended rate of 11 kg Zn ha^{-1} for granular Zn fertilizers (Slaton, 2001).

Plot level data were averaged across replications for each Zn source and application rate combination to compare the immediate (2000) and residual (2001) effects of the four Zn fertilizer sources on rice growth and yield and Mehlich-3 extractable Zn. Rice tissue Zn concentrations and grain yields were initially regressed on Zn fertilizer rate using a quadratic model in which coefficients were allowed to differ by Zn source. Depending on the results of the initial fit, nonsignificant ($P >$ 0.05) model terms were eliminated sequentially until a suitable final model was obtained for each site-year combination. All statistical analyses were performed using SAS version 8.2 (SAS Institute, Inc., Cary, NC).

RESULTS

Rice Response to Zinc Fertilization

Rice dry matter accumulation, tissue Zn concentration, aboveground Zn uptake, and grain yield were all increased by application of 13.5 kg Zn ha^{-1}, when averaged across the four Zn fertilizer sources, during 2000 and 2001 (Table 3). For all site-years, rice seedlings receiving no Zn fertilizer contained <15 to 20 mg Zn kg^{-1}, which is the established critical range for tissue Zn concentration (Norman et al., 2003).

Zinc deficiency symptoms, including bronzing of the older leaves, chlorosis and necrosis of young leaves, and stunted growth (Norman et al., 2003), were observed in rice receiving <9 kg Zn ha^{-1} at the RREC during both years with the frequency and severity of symptoms increasing as Zn fertilization rate declined. At the PTBS, the typical leaf discolorations associated with Zn-deficient rice were not observed despite relatively low tissue Zn concentrations. However, as evidenced by dry matter accumulation, there were visually distinguishable growth differences between rice receiving (+Zn) and

Table 3. Single-degree-of-freedom contrasts comparing the effect of Zn application rates of 0 (−Zn) and 13.5 (+Zn) kg Zn ha^{-1}, averaged across four Zn fertilizer sources, on rice grain yield and dry matter accumulation, tissue Zn concentration, and total Zn uptake 11 to 14 d after flooding at the Pine Tree Branch Station (PTBS) and Rice Research Extension Center (RREC) during 2000 and 2001.

		PTBS 2000†		PTBS 2001†		RREC 2000†		RREC 2001†	
Parameter	Units	− Zn	+ Zn	− Zn	+ Zn	− Zn	+ Zn	− Zn	+ Zn
Grain yield	kg ha^{-1}	7309 b	8658 a	7277 b	8057 a	5177 b	6090 a	2863 b	6906 a
Dry matter	kg ha^{-1}	278 b	469 a	776 b	1030 a	199 b	590 a	391 b	876 a
Tissue Zn	mg Zn kg^{-1}	15.1 b	21.0 a	15.6 b	23.5 a	13.9 b	21.5 a	12.4 b	17.9 a
Zn uptake	g Zn ha^{-1}	4.3 b	10.1 a	12.7 b	24.4 a	2.7 b	13.8 a	5.0 b	16.5 a

† For each measurement within a site-year, Zn treatment means followed by different letters signify statistical differences ($P \leq 0.05$).

Table 4. Analysis of variance *p* values for final regression models for tissue dry matter, Zn concentration, and grain yield as affected by Zn fertilizer source, Zn fertilizer rate, and their interactions for studies conducted in 2000 and 2001 at the Pine Tree Branch Station (PTBS) and Rice Research Extension Center (RREC).

	2000		2001	
Parameter-source	**PTBS**	**RREC**	**PTBS**	**RREC**
	p-value			
	Dry matter			
Common intercept different from 0	<0.0001	–	<0.0001	0.0019
Intercepts differ by Zn source	–	0.1674	0.3657	–
Common linear coefficient different from 0	0.0098	–	0.5420	0.0078
Linear coefficients differ by Zn source	–	0.0085	0.2489	–
Common quadratic coefficient different from 0	–	–	0.6320	0.0337
Quadratic coefficients differ by Zn source	–	0.0060	0.2067	–
	Tissue Zn Concentration			
Common intercept different from 0	–	–	<0.0001	<0.0001
Intercepts differ by Zn source	0.0251	0.8745	–	–
Common linear coefficient different from 0	<0.0001	–	<0.0001	<0.0001
Linear coefficients differ by Zn source	–	0.0055	–	–
Common quadratic coefficient different from 0	–	–	–	–
Quadratic coefficients differ by Zn source	–	–	–	–
	Grain Yield			
Common intercept different from 0	<0.0001	–	<0.0001	<0.0001
Intercepts differ by Zn source	–	0.0190	–	–
Common linear coefficient different from 0	0.0161	–	0.0050	0.0008
Linear coefficients differ by Zn source	–	0.0171	–	–
Common quadratic coefficient different from 0	0.0398	–	–	0.0168
Quadratic coefficients differ by Zn source	–	0.0184	–	–

not receiving (−Zn) preplant Zn. Zinc deficiency at the PTBS was characterized by the lack of vigorous growth after N fertilization and flooding and can be considered moderate Zn deficient. Although the percentage of yield increases were similar between sites in 2000, dry matter and total Zn accumulation data indicate that soil Zn availability was a greater limitation to early season plant growth at the RREC and can be characterized as moderate to severe.

All four site-years responded positively to 13.5 kg Zn ha^{-1}. Therefore, these studies are suitable to evaluate whether specific Zn-fertilization recommendations are required for Zn fertilizers that differ in chemical and/or physical properties, which may influence the immediate, residual, or immediate and residual fertilizer-Zn availability to field-grown rice. Previous research performed with seedling plants in the greenhouse suggests that selection of an appropriate commercially available Zn source is an important fertilization decision (Amrani et al., 1999; Gangloff et al., 2002; Giordano and Mortvedt, 1969; Mortvedt, 1992).

Year 1—Dry Matter Accumulation

At the PTBS, rice dry matter accumulation increased linearly as Zn application rate increased (Table 4; Fig. 1) and was not affected by Zn source. Although dry matter accumulation response to Zn fertilizer rate was significant, only relatively small increases in dry matter were obtained from Zn fertilization. This suggests that Zn nutrition was not a great growth-limiting factor and, apparently, all four Zn sources are capable of maximizing early season plant growth when Zn deficiency is relatively moderate.

At the RREC, the Zn source × Zn rate (quadratic interaction) was significant (Table 4). Dry matter accumulation of rice fertilized with ZnSul31, ZnLig10, and ZnOxy20 increased nonlinearly with near maximum dry matter produced at Zn application rates of 9 to 13.5 kg Zn ha^{-1} (Fig. 1). For ZnOxy36, the linear and nonlinear coefficients were not statistically significant indicating that it behaved differently from the other Zn sources. However, dry matter accumulation of rice fertilized with ZnOxy36 did increase incrementally as Zn application rate increased. The trends among Zn sources at this site suggest that a higher Zn fertilizer rate is required to maximize early season growth with ZnOxy36 than with the other three Zn sources, which contained greater levels of WsZn (Table 2), when Zn deficiency is quite severe.

Year 1—Tissue Zinc Concentration

Whole-seedling Zn concentrations were significantly affected by Zn fertilization during 2000, the year that Zn was applied, at both the PTBS and RREC (Table 4, Fig. 2). At the PTBS, tissue Zn concentration was affected by the main effects of Zn source and application rate (Table 4). For all Zn sources, tissue Zn concentration increased linearly at a common rate as Zn fertilizer rate increased from 2.3 to 18.0 kg Zn ha^{-1}, however the magnitude of tissue Zn concentration (i.e., intercept) differed among sources (Table 4; Fig. 2). Within each application rate tissue Zn concentration generally decreased as the fertilizer WsZn content decreased. Rice fertilized with ZnLig10, ZnOxy20, and ZnSul31 contained similar Zn concentrations that were greater than the Zn concentrations of rice fertilized with ZnOxy36.

The Zn source × application rate (linear) interaction was significant at the RREC (Table 4). For all Zn sources, except ZnOxy36, tissue Zn concentration increased linearly as Zn application rate increased, but the rate of increase (slope) varied among Zn sources (Table 4, Fig. 2). The rate of increase in tissue Zn concentration followed the general order of ZnLig10 = ZnSul31 >

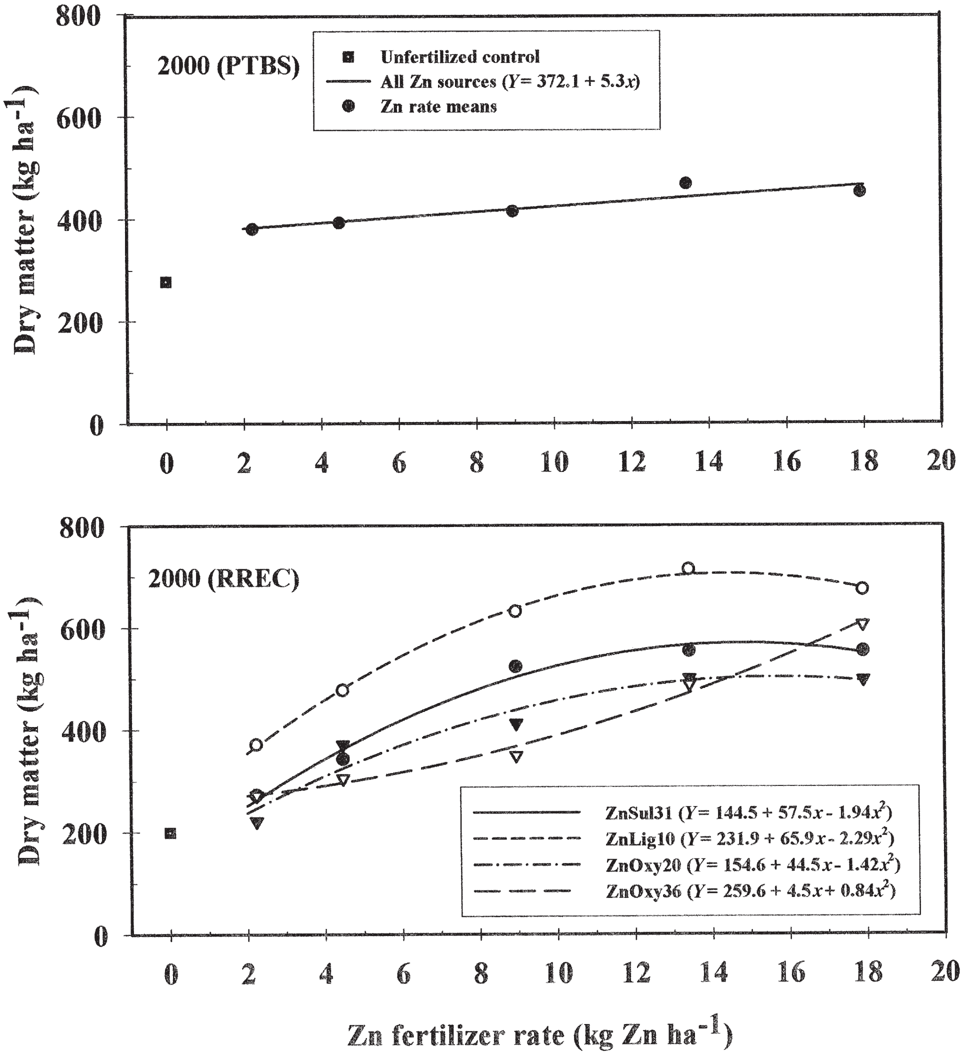

Fig. 1. Predicted aboveground dry matter accumulation of rice at the midtillering stage as affected by Zn fertilizer source and application rate during 2000 at the Pine Tree Branch Station (PTBS) and Rice Research Extension Center (RREC). For reference, the mean dry matter accumulations for the unfertilized controls (0 kg Zn ha^{-1}) are shown as ■. For the RREC, mean dry matter values are shown as ● for zinc sulfate 31% Zn (ZnSul31), ○ for zinc lignosulfonate 10% Zn (ZnLig10), ▼ for zinc oxysulfate 20% Zn (ZnOxy20), and ▽ for zinc oxysulfate 36% Zn (ZnOxy36). For the PTBS, standard errors were 20.1 for intercept and 1.8 for linear coefficient. For the RREC, standard errors were 38.4 for intercept, 9.6 for linear coefficient, and 0.47 for the quadratic coefficient.

ZnOxy20 > ZnOxy36 showing that as the fertilizer WsZn content decreased (Table 2) the rate of increase for tissue Zn concentration also decreased.

Year 1—Grain Yield

In 2000, Zn fertilizer source had no significant influence on rice grain yield at the PTBS (Table 4). Only Zn fertilizer rate significantly influenced rice grain yield at the PTBS, which showed moderate response to Zn fertilization (Table 3). Grain yields increased nonlinearly (i.e., quadratic) as Zn fertilizer rate increased (Fig. 3). Near maximum grain yields were produced when the Zn application rate ranged from 9 to 13.5 kg Zn ha^{-1}, which encompasses the recommended rate (11 kg Zn ha^{-1}, Slaton, 2001) for granular Zn fertilizers applied preplant. Compared with the unfertilized control (7309 kg ha^{-1}), Zn fertilization increased rice grain yields by 890 to 1432 kg ha^{-1}.

The effects of application rate differed significantly among Zn sources at the RREC in 2000 (Table 4). The linear and nonlinear coefficients for ZnSul31, ZnLig10, and ZnOxy36 were not significant indicating that grain yields did not increase or decrease significantly due to Zn application rate. Only the intercepts were significant for these Zn sources indicating differences in the mean yields. A significant nonlinear trend was observed only for rice grain yields receiving ZnOxy20 (Fig. 3). The absence of consistent grain yield responses to Zn rate and Zn source were due to an unknown source of floret sterility that was present in all treatments. Floret sterility likely prevented rice from realizing its full yield potential as influenced by Zn fertilization and resulted in lower than expected grain yields for rice receiving adequate amounts of Zn fertilizer. Because the floret sterility was present in all Zn treatments the cause could not be attributed to Zn deficiency or a specific Zn source.

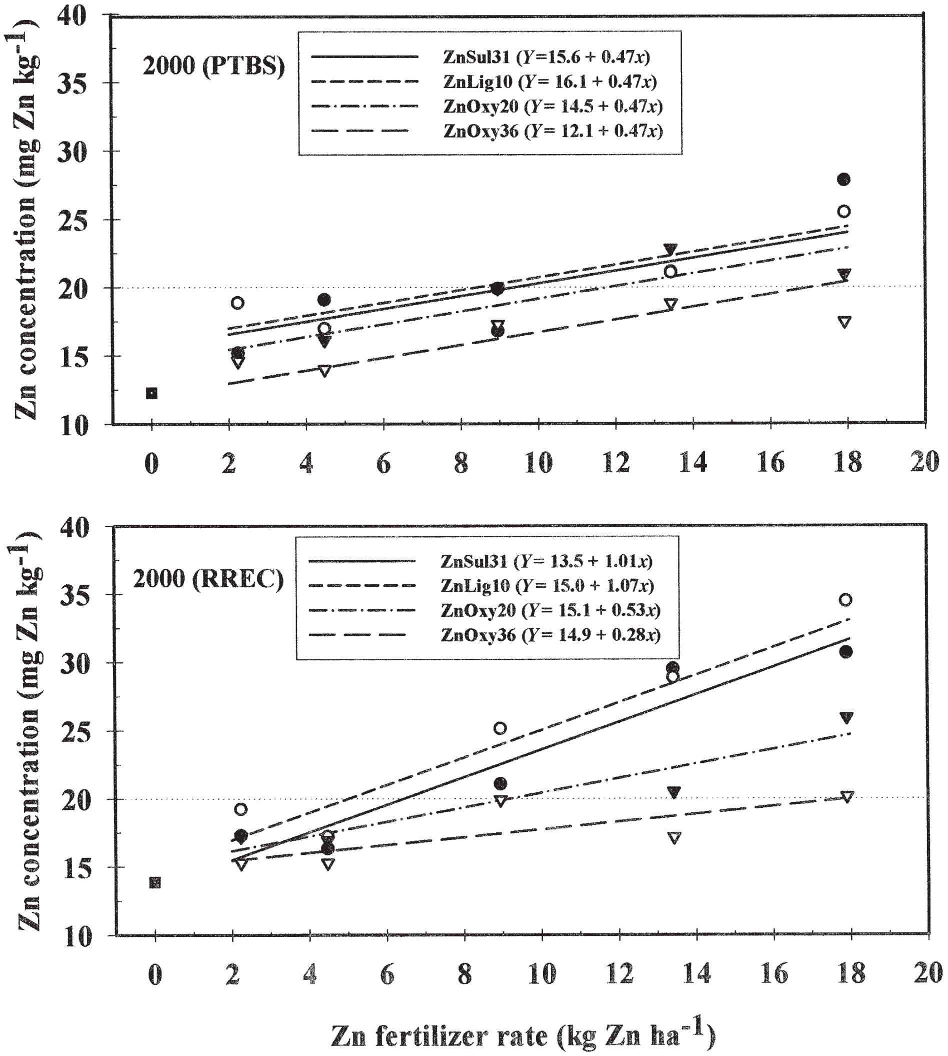

Fig. 2. Predicted tissue Zn concentration of rice at the midtillering stage as affected by Zn fertilizer source and application rate during 2000 at the Pine Tree Branch Station (PTBS) and Rice Research Extension Center (RREC). For reference, the dashed horizontal line (20 mg Zn kg^{-1}) represents the critical Zn concentration. Mean Zn concentrations are shown as ■ for the unfertilized control (0 kg Zn ha^{-1}), ● for zinc sulfate 31% Zn (ZnSul31), ○ for zinc lignosulfonate 10% Zn (ZnLig10), ▼ for zinc oxysulfate 20% Zn (ZnOxy20), and ▽ for zinc oxysulfate 36% Zn (ZnOxy36). For the PTBS, standard errors were 1.5 for intercept and 0.08 for linear coefficient. For the RREC, standard errors were 1.6 for intercept and 0.14 for linear coefficient.

Despite the sterility, Zn fertilization generally increased rice grain yields compared with the unfertilized control. The sterility did not influence vegetative growth when rice was sampled 12 DAF.

Year 2—Tissue Zinc Concentration and Grain Yield

In 2001, the second cropping year after Zn was applied, Zn fertilizer source had no influence on seedling Zn concentrations, dry matter accumulation, or grain yield at the PTBS or RREC (Table 4). Tissue Zn concentration increased linearly as the previous year's Zn application rate increased at both sites (Table 5). Dry matter accumulation of seedling rice was not affected by Zn fertilization at the PTBS, where rice growth and yield increases to Zn fertilization during the first year were significant, but moderate. In contrast, at the RREC, dry matter accumulation followed a nonlinear trend and was affected only by Zn application rate (Tables 4 and 5).

Grain yields increased linearly at the PTBS and nonlinearly at the RREC as Zn fertilizer rate increased, when averaged across Zn fertilizer sources (Tables 4 and 5). At the PTBS, application of all Zn rates increased grain yields by 483 to 830 kg ha^{-1} (7–11%) above the unfertilized control. The yield response to Zn fertilization at the RREC was much greater with Zn fertilization increasing rice grain yields by 2381 to 4244 kg Zn ha^{-1} (83–148%) above the unfertilized control. Although no Zn was applied (i.e., as a reference treatment) in 2001, yield data suggest that maximum or near maximum yields were produced at both locations. Based on the composite soil samples taken before flooding in 2001 and soil-test based Zn fertilizer recommendations (Slaton, 2001), Mehlich-3 extractable Zn was adequate (>3.5 mg Zn kg^{-1}) in treatments receiving ≥13.5 kg Zn

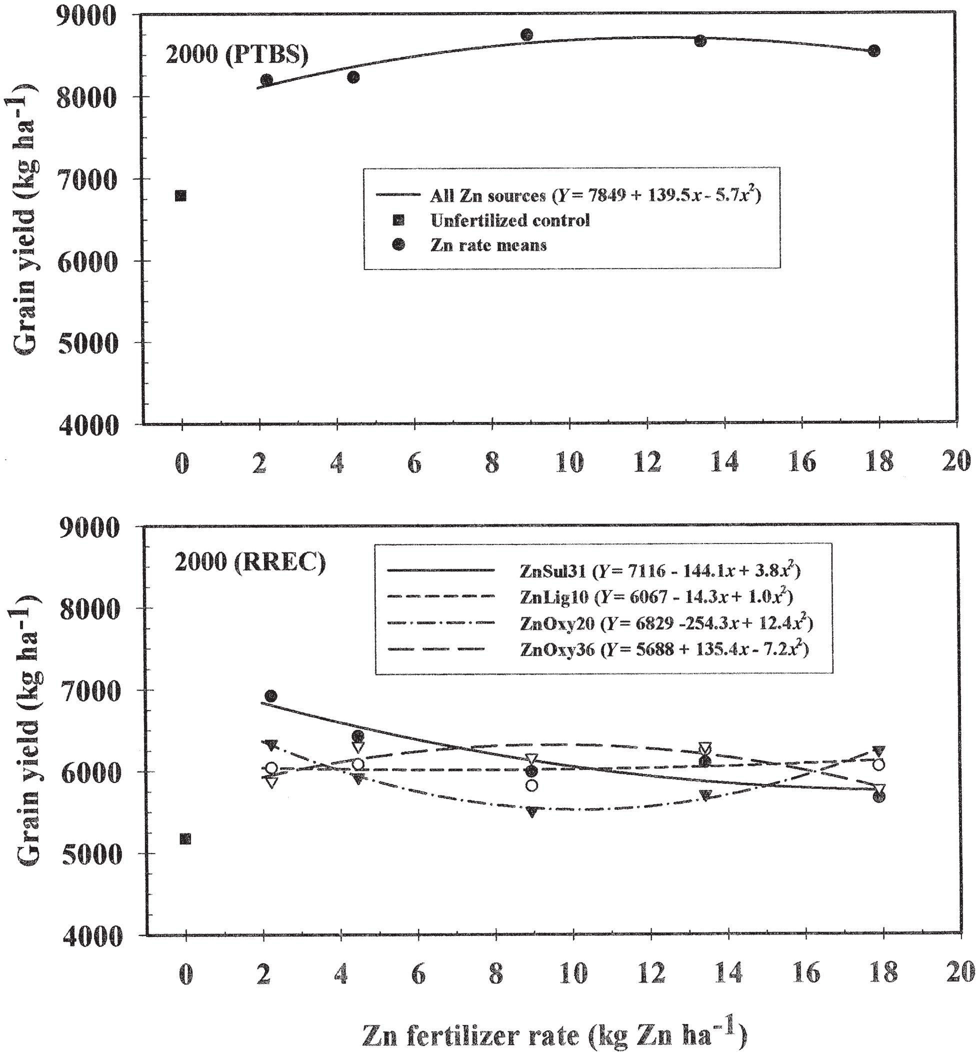

Fig. 3. Predicted grain yield of rice as affected by Zn fertilizer source and application rate during 2000 at the Pine Tree Branch Station (PTBS) and Rice Research Extension Center (RREC). For reference, the mean grain yields for the unfertilized controls (0 kg Zn ha^{-1}) are shown as ■. For the RREC, mean grain yields are shown as ● for zinc sulfate 31% Zn (ZnSul31), ○ for zinc lignosulfonate 10% Zn (ZnLig10), ▼ for zinc oxysulfate 20% Zn (ZnOxy20), and ▽ for zinc oxysulfate 36% Zn (ZnOxy36). For the PTBS, standard errors were 209 for intercept, 52.2 for linear coefficient, and 2.6 for quadratic coefficient. For the RREC, standard errors were 270 for intercept, 67.2 for linear coefficient, and 3.3 for quadratic coefficient.

ha^{-1} at both sites. Composite soil samples taken from each treatment replicate 1 yr after Zn fertilization showed that Zn source had no influence on Mehlich-3 extractable soil Zn (Table 5). Mehlich-3 extractable soil Zn increased linearly as Zn application rate increased at both sites. Although the slopes between sites were not compared statistically, the rate of increase in Mehlich-3 extractable Zn increased at numerically comparable rates.

DISCUSSION

Total aboveground Zn uptake and tissue Zn concentration of seedlings are measures of the relative Zn availability to plants of each fertilizer source. For the year that the Zn fertilizers were applied (2000), the Zn concentration of field-grown rice varied among Zn sources and supports the conclusions from greenhouse studies that the level of WsZn is an important consideration when selecting a Zn fertilizer (Amrani et al., 1999; Gangloff et al., 2002; Giordano and Mortvedt, 1969; Liscano et al., 2000; Mortvedt, 1992). Similar to Mortvedt (1992) and Amrani et al. (1999), our data for field-grown rice suggests that when the level of WsZn is <40%, the growth and Zn nutritional status of rice grown on Zn-deficient soils are compromised. Because greenhouse and field data show similar trends, data from greenhouse studies can be used to ascertain the relative effectiveness of various Zn fertilizers and application rates for field-grown crops. However, our data also suggests that differences in tissue Zn concentrations of seedling crops attributed to Zn source may not always produce significant grain yield differences among Zn sources at maturity. Although granular Zn sources clearly differ in their ability to provide available Zn to the first crop, all four sources supplied sufficient available Zn to produce near maximum yields when early season Zn deficiency was not severe.

Table 5. Regression coefficients for rice dry matter, tissue Zn concentration, grain yield, and Mehlich-3 extractable soil Zn measured in 2001 to evaluate the residual effect of Zn fertilizer treatments at the Pine Tree Branch Station (PTBS) and Rice Research Extension Center (RREC).

	PTBS 2001		RREC 2001		
Parameter/Zn source	Intercept	Linear	Intercept	Linear	Quadratic
Dry matter					
All Zn sources	945.1	–	349.8	71.7	−2.7
Standard error	22.1	–	95.4	23.8	1.2
Tissue Zn concentration					
All Zn sources	16.8	0.44	13.2	0.38	–
Standard error	0.8	0.07	0.5	0.05	–
Grain yield					
All Zn sources	7726.1	22.1	4728.0	301.4	−9.6
Standard error	75.9	6.9	297.1	74.1	3.6
Mehlich-3 Soil Zn					
All Zn sources	1.6	0.23	1.5	0.20	–
Standard error	0.3	0.03	0.2	0.03	–

Giordano and Mortvedt (1972) showed that Zn from the highly soluble $ZnSO_4$ was more mobile in the soil profile than Zn from insoluble ZnO. Differences in Zn mobility in soil are undoubtedly related to the fertilizer WsZn level. Greater dissolution of Zn from fertilizers with high levels of WsZn would enhance the diffusion rate and, hence, fertilizer Zn uptake by seedling crops which have small root systems. This is an important factor considering that the need for Zn fertilization is greatest on alkaline soils and fertilizer Zn mobility decreases as soil pH increases (Mortvedt and Giordano, 1967).

Giordano and Mortvedt (1972) also showed that flood-irrigated rice had greater Zn uptake than rice grown under moist soil conditions and that the downward movement of Zn from ZnO, but not $ZnSO_4$, was greater in flooded soils than moist soils. These results hint that flooded soil conditions may increase the movement of Zn from low and moderately soluble Zn fertilizers in soil such that differences in Zn fertilizer physical and chemical properties may be less important for flood-irrigated rice than for upland crops such as corn.

After application, fertilizer Zn reacts with the soil and is converted into more stable compounds that are less available to plants. These reactions are perceived to be rapid enough that they may limit the effectiveness of highly soluble inorganic Zn fertilizers (Boawn et al., 1957). However, fractionation of Zn-fertilized non-calcareous soils has shown that a significant proportion of the fertilizer Zn remains in the exchangeable and organically complexed soil Zn pools, which are considered plant available, for at least 60 d after soil application (Alvarez et al., 2001). Mortvedt and Giordano (1967) also showed that exchangeable soil Zn was increased for at least 8 wk after the application of $ZnSO_4$ with various macronutrient carriers, however the exchangeable Zn fraction decreased more rapidly with time as soil pH increased. Obrador et al. (2003) showed that a Zn fertilizer chelated with amino acids failed to increase the exchangeable and organically complexed soil-Zn pools when analyzed 15 to 60 d after application on a highly calcareous soil, but a synthetically chelated Zn product significantly increased these plant-available Zn pools. They hypothesized that the behavior of the amino acid chelation was too weak to protect the Zn^{2+} from being retained by amorphous and crystalline Fe oxides, and could be likened to the behavior of $ZnSO_4$ or Zn-lignosulfonate fertilizers in calcareous soils. Previous research suggests that the behavior of Zn fertilizer, when mixed with soil, is clearly influenced by soil pH, as well as the presence and amount of free $CaCO_3$ in the soil. Thus, the chemical properties and application rates of Zn fertilizers that are deemed ideal for non-calcareous may be less desirable for highly calcareous soils.

The physical properties of Zn fertilizers are also known to influence crop response to Zn fertilization. Goos et al. (2000) showed that crop growth and Zn uptake were similar for $ZnSO_4$ and Zn-lignosulfonate, applied at equal rates, when their physical form (i.e., granules) was similar. Zinc uptake was markedly improved for both sources by crushing the granules into a powder. Liscano et al. (2000) and Giordano and Mortvedt (1966) also showed that increased fertilizer granule number (i.e., decreased granule size while maintaining Zn rate) increased plant uptake of Zn, presumably from increased distribution of Zn in the soil. Furthermore, Giordano and Mortvedt (1966) showed that the distance of Zn movement was independent of the Zn concentration in the fertilizer granule. Zinc fertilizers that have low Zn concentrations, small granule size, or both would influence a greater volume of soil than fertilizers with high Zn concentrations and/or large granules when applied at equal Zn rates. Reducing the fertilizer granule size and Zn concentration may improve Zn availability from sources with low levels of WsZn (Liscano et al., 2000).

Powdered ZnO has produced equal or superior Zn nutrition and plant growth to granulated $ZnSO_4$ in several greenhouse studies (Amer et al., 1980; Mortvedt, 1992). In our study, the predominant fertilizer granule sizes tended to increase as fertilizer WsZn decreased, which prevented separate evaluations for the effect of granule distribution and fertilizer WsZn on Zn nutrition of rice. However, our data should accurately reflect the performance of these four commercial fertilizers under field situations. Reducing the fertilizer granule size, Zn concentration, or both are potential ways for Zn manufacturers to enhance Zn distribution and ultimately improve the short-term performance of fertilizers with low WsZn levels.

The most unique aspect of this study was that we evaluated the immediate and residual effectiveness of commercially available Zn fertilizers on the Zn nutritional status of field-grown rice. Previous studies have generally focused on the immediate Zn availability from fertilizers having different levels of WsZn (Amrani et al., 1999; Gangloff et al., 2002; Giordano and Mortvedt, 1969; Liscano et al., 2000; Mortvedt, 1992) or on the residual effect of Zn application rate on crop growth and nutrition (Boswell et al., 1989; Brown et al., 1964; Carsky and Reid, 1990). A single application of a sufficient Zn fertilizer rate is known to increase soil-test Zn and provide adequate Zn nutrition for several years (Boswell et al., 1989; Carsky and Reid, 1990). However, the effect of fertilizer properties on residual Zn availability has not been thoroughly evaluated.

Goos et al. (2000) showed that Zn fertilizer granule size greatly affected the growth and Zn nutrition of the first crop, but had little or no influence on the second crop. Similarly, during the second year after Zn was applied in our study, the physical and chemical properties of the four Zn fertilizers had no significant effect on the Zn nutritional status or grain yield of rice (Table 5). Mehlich-3 extractable Zn also increased at a uniform rate among Zn sources as Zn application rate increased. These data all suggest that while the chemical properties of Zn fertilizers influence the Zn nutrition and yield potential of crops grown immediately after application, Zn in fertilizers low in WsZn is released within 1 yr after application. Because routine soil-test methods such as Mehlich-3 and DTPA are well correlated with crop response to Zn fertilization it is reasonable to assume that they reflect the plant-available pool of soil Zn.

One possible solution that could simplify recommendations and account for differences among granular Zn fertilizers is to express recommended Zn rates as the amount of WsZn, rather than elemental Zn rates. The relationships between aboveground Zn uptake by rice at the midtillering stage with the rate of broadcast-applied WsZn were highly significant (all coefficient p values < 0.05) and linear at the PTBS and nonlinear at the RREC (Fig. 4). Application of 6 to 8 kg WsZn ha^{-1} produced near maximum rice dry matter accumulations and tended to increase whole-plant Zn concentrations above the 20 mg Zn kg^{-1} critical concentration at both sites in 2000 (data not shown). These recommendations would require that (i) recommended rates of elemental Zn were based on research conducted with Zn fertilizers with known levels of water-soluble Zn (i.e., a standard reference), (ii) the WsZn levels of commercially available Zn fertilizers are known, (iii) the residual benefits of Zn fertilization are recognized, regardless of the Zn source (i.e., level of WsZn), and (iv) agricultural consultants, fertilizers dealers, and growers are educated on the use of such recommendations.

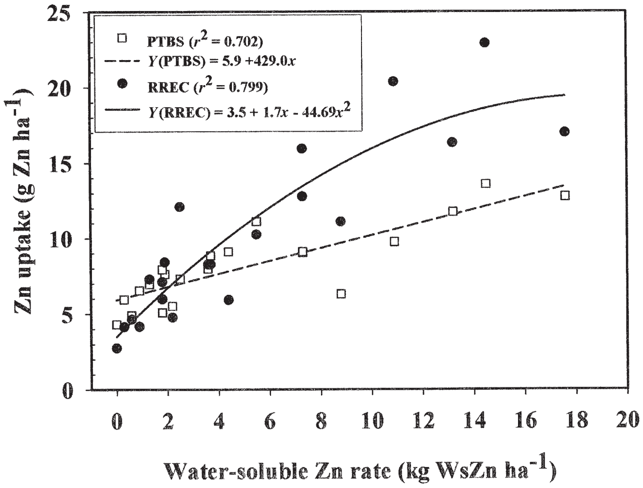

Fig. 4. The relationships between water-soluble Zn application rate with aboveground Zn uptake by rice at the midtillering growth stage for studies conducted in 2000 at the Pine Tree Branch Station (PTBS) and Rice Research Extension Center (RREC).

SUMMARY

Our field data supported research conclusions from several greenhouse studies, which showed that granular Zn fertilizer source might influence the growth and Zn nutrition of the crop grown immediately following Zn fertilization. Zinc fertilizer source affected early season rice growth and Zn nutrition, but not grain yield, only for the rice crop grown immediately after fertilization. The residual benefits of Zn fertilization on rice growth, Zn nutrition, and grain yield were not affected by Zn fertilizer source, but were affected by Zn application rate. Apparently, the chemical reactions between Zn fertilizers and soil are sufficiently complete by 1 yr after fertilization so that soil properties, rather than fertilizer properties, control the residual Zn availability to plants, which can be accounted for through soil testing.

The selection of an appropriate Zn source is most critical only for the crop to be grown the same year that Zn fertilizer is applied. All four of the Zn sources can be considered sufficient fertilizers so long as the proper Zn rate is applied. Growers should be made aware through university recommendations that granular Zn fertilizers with low WsZn levels may not contain sufficient immediately available Zn to maximize seedling growth and Zn nutrition, especially if low rates of Zn are broadcast applied. Because fertilizer WsZn level has consistently shown to be a reliable indicator of the immediately available Zn and analysis for fertilizer WsZn can be performed by most laboratories for a modest cost, fertilizer use guidelines can be established for the commercially available Zn fertilizers for any given region. Fertilization guidelines need not discriminate against the use of fertilizers with low (<40–50%) WsZn levels on non-calcareous, Zn-deficient soils, but should make growers aware of the potential advantages and disadvantages of the available fertilizers. Recommendations can (i) identify fertilizer sources that have high levels of WsZn and will provide sufficient plant-available Zn at the recommended Zn application rates and (ii) identify Zn fertilizers that contain low levels of WsZn and suggest rate adjustments (i.e., increases) that will provide sufficient plant-available Zn for the crop to be grown. The retail prices and recommended application rates of commercially available Zn fertilizers will provide growers with greater options to establish sound

Zn fertilization programs that provide adequate Zn nutrition to crops on the short- and long-terms. For Zn sources with low WsZn content, higher Zn application rates would need to be applied to achieve similar tissue Zn concentrations in the year of application as a source with a high level of WsZn.

Field and greenhouse research studies are usually conducted on Zn-deficient soils, however they may not always represent the most Zn-deficient soils or duplicate other environmental (i.e., cool temperatures) and pest induced (i.e., inhibited root growth and root pruning) stresses that can occur in commercial production fields. Thus, the fertilizer sources or source and rate combinations that provide superior nutrient availability should be recommended so that maximum crop growth and yield potential can be realized.

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