Zinc Fertilization: A Review of Scientific Literature

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Introduction

Micronutrients are very important to plant health and contribute greatly to yield, which is the main concern for much of the agricultural industry. One of the more important micronutrients is zinc (Zn). Zinc deficient soil can be found throughout the world and are normally associated with low soil organic matter and a soil pH higher than 7.0. Zinc deficiencies are corrected in most cases by applying a granular Zn fertilizer or applying it with the starter macronutrient (NPK) fertilizer either as a coating or incorporated into the macronutrient granule. Granules of either the Zn or NPK fertilizer are then either broadcast and incorporated into the soil or band applied to the soil below and to the side of the seed rows.

Historically, zinc sulfate ($ZnSO_4$) has been the Zn source of choice. However there are other alternatives for Zn sources, some of which make claims of increased efficiency of Zn availability to the plant. The purpose of this literature review was to summarize and evaluate pertinent research and scientific literature comparing the relative availability coefficients of Zn fertilizers as well as those that compare Zn availability when applied by different methods.

As stated above, other sources of Zn exist and many are derived from industrial by-products, varying from flue dust reacted with sulfuric acid to organic compounds derived from the paper industry. Some of these other common choices for Zn include:

- Zinc Sulfate

  Zinc sulfate ($ZnSO_4$) monohydrate is produced by adding sulfuric acid to ZnO (Zn oxide), followed by dehydration to form $ZnSO_4 \bullet H_2O$. Most sources contain about 35% total Zn and 98% water-soluble Zn.
- Zinc Oxide

  Zinc oxide (ZnO) is a common inorganic salt of Zn derived from many industrial processes. ZnO can range from 70 to 80% total Zn but is less soluble than $ZnSO_4$
- Zinc EDTA

  Zinc EDTA (ZnEDTA), a chelate[1], is a liquid Zn fertilizer (9% total Zn) that is often added to tanks during fertilizer formation. ZnEDTA is 100% water-soluble Zn.
- Zinc Oxysulfates

  Zinc oxysulfates (ZnOx) are formed by adding H_2SO_4 to Zn feedstocks. These feedstocks are commonly ZnO industrial byproducts. The water solubility of these fertilizer materials is variable and is related to the amount of H_2SO_4 added during the manufacturing process.

[1] A chelating agent is a compound containing donor atoms that can combine with a single metal ion to form a cyclic structure called a chelation complex, or more simply, a chelate (Mortvedt, 1985)

- Zinc Lignosulfonate

  Zinc lignosulfonate (ZnLigno) is a complexed[2] organic Zn fertilizer that is formed by reacting $ZnSO_4$ with lignin wastes produced by the paper industry. Most sources contain 10% to 20% total Zn and 91% of the total Zn as water-soluble.
- Zinc Sucrate

  Zinc sucrate (ZnSuc) is a complexed[2] organic Zn fertilizer that is formed by reacting sucrose-type materials (e.g. cane sugar molasses) with ZnO. Most sources are 38% total Zn and <1% water-soluble.

Zinc Relative Availability Coefficients and Water-Solubility

Relative availability coefficients (RAC) allow one to compare equally different sources of Zn fertilizer over the application range. There is no absolute numerical value for an RAC but rather they are measurements relative to the Zn source that had the highest response to dry matter production, Zn concentration, and/or Zn uptake. A greenhouse study on corn conducted by Gangloff *et al* (2002), compared several Zn fertilizers in soil limed to a pH of 7.2. The RAC were calculated using the following equation as described by Boawn (1973):

RAC% = (Slope of material in question / Reference slope) * 100

Gangloff *et al* (2000) found that $ZnSO_4$, Zn lignosulfonate and ZnEDTA all produced similar increases of dry matter (15-21%) when compared to the control, which had no Zn fertilizer applied (Table 1). Two Zn oxysulfates (26 and 55% water soluble) both increased dry matter by about 9% and ZnSuc only increased dry matter by 4%, which was not significantly different than the control. Statistical analysis was performed that indicated there was significance between the rates within the Zn sources. Also, the Zn lignosulfonate, ZnEDTA, $ZnSO_4$, and the Zn oxysulfate (55% water-soluble) all performed equally well. The Zn lignosulfonate outperformed the Zn oxysulfate (26% water-soluble). Finally, Zn sucrate was outperformed by Zn lignosulfonate, $ZnSO_4$, and ZnEDTA, but was not different than either of the Zn oxysulfates.

Table 1. Relative Availability Coefficients (RAC), as determined by the Slope of the Regression Equation for Dry Matter Production, Zn Concentration and Uptake (Gangloff *et al*, 2002)

	Dry Matter		Zn Concentration			Zn Uptake		
Zn Fertilizer	Slope	RAC%	Slope	RAC%	RAC%[a]	Slope	RAC%	RAC%[a]
ZnEDTA	0.306	70	3.640	100	–	0.0615	100	–
$ZnSO_4$	0.338	77	0.687	19	100	0.0143	23	100
ZnLigno	0.438	100	0.646	18	94	0.0134	22	94
ZnOx26	0.160	37	– 0.085	– 2	– 12	0.0002	0.5	1
ZnOx55	0.263	60	0.343	9	50	0.0077	12	48
ZnSuc	0.062	14	0.173	5	25	0.0030	5	21

[a]RAC values in this column are based on $ZnSO_4$ as the reference slope.

[2] Natural organic complexes, such as lignosulfonates, phenols, and ployflavenoids, are produced by reacting metallic salts with organic byproducts of the wood pulp industry. The type of chemical bonding of the metals to organic components is not well understood (Mortvedt, 1985).

In this same study, Zn concentration in plant tissue was measured and it was found that the fertilizers fell into three groups: 1) ZnEDTA had the greatest plant concentration; 2) $ZnSO_4$ and Zn lignosulfonate were similar and lower than ZnEDTA; and 3) the remaining fertilizer sources had moderate to low Zn concentration that were significantly lower than the previous two groups (Fig 1-3).

Finally, Zn uptake was calculated was found to be similar to concentration. From these three measurements, RAC were calculated using the above equation and summarized in Table 1. It was also concluded that the RAC values were highly correlated with water-solubility of the Zn source. The plant availability from these Zn sources was directly related to the water-solubility. Zinc sources with high water-solubility had a high relative availability and those with low water-solubility had a low relative availability.

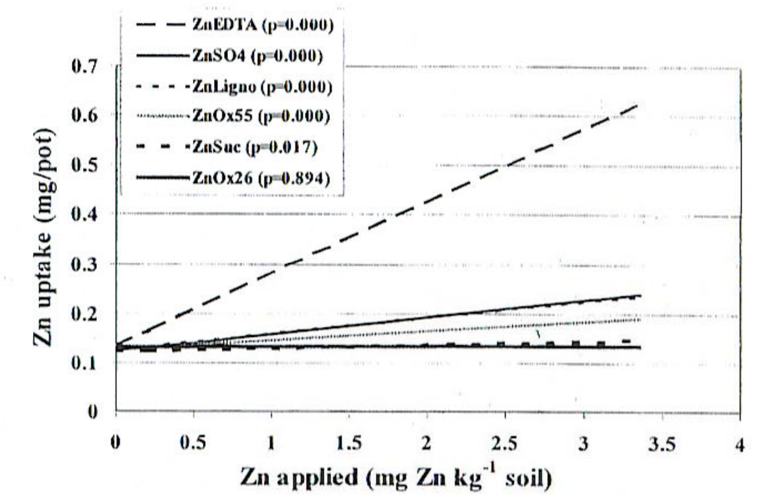

Figure 3. Regression of Zn uptake (mg/pat) of corn as affected by Zn source and rate.

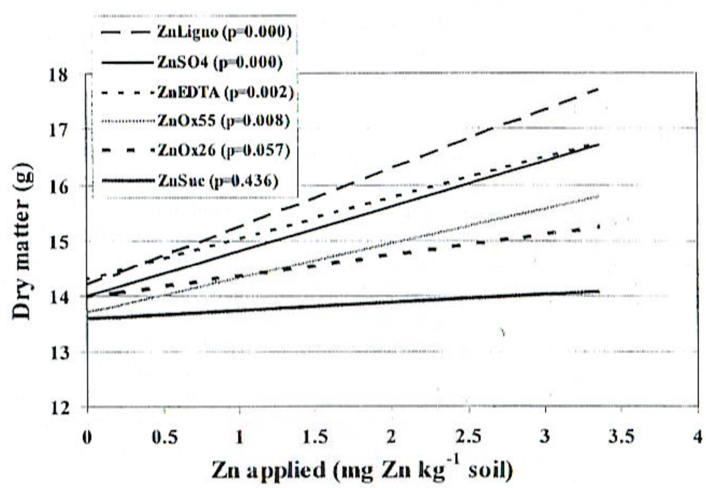

Figure 1. Regression of corn dry matter production as affected by Zn source and rate.

(Gangloff, *et al*, 2002)

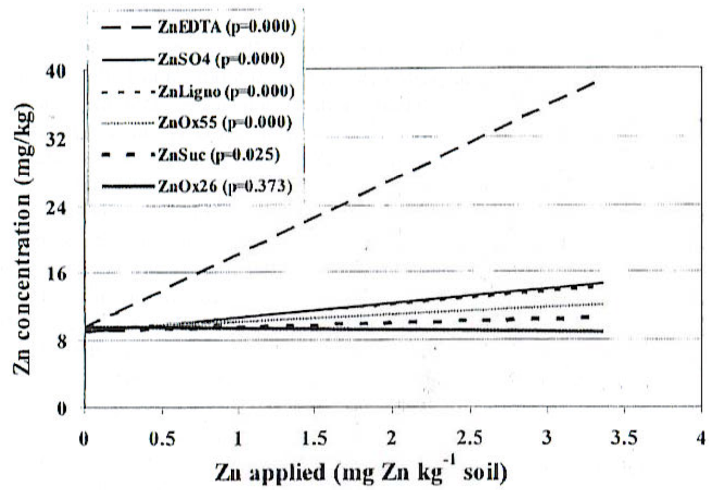

Figure 2. Regression of Zn concentration (mg/kg) of corn as affected by Zn source and rate.

(Gangloff *et al*, 2002)

Other researchers reported similar results. Amrani *et al* (1999) conducted a similar study earlier in soil at pH 6.3 and 7.4 and found that dry matter production, plant concentration, and plant uptake was a function of water solubility and developed equations describing these relationships. It was also concluded from that study that at least 50% of the total Zn be water-soluble. Similarly, Mortvedt (1992) found that 40% of the total Zn needed to be water-soluble. Westfall *et al* (2005) also found a very strong correlation (r^2 =0.92) between Zn availability and water-solubility and not total Zn content of the fertilizer.

This relationship holds true in other areas of the country for other crops as well. Liscanso *et al* (2000) conducted an experiment studying the availability of different granular Zn fertilizers on rice plants in Arkansas in a soil limed to a pH of 7.5. They concluded that granular sources with 54% or more of the total Zn as water-soluble Zn corrected Zn deficiency in rice when applied at an 11.2 kg/ha rate. They also tested different extraction methods and found that the water-soluble fraction best described the plant uptake of Zn. Judy *et al* (1964) also found in Michigan that $ZnSO_4$ and powdered ZnO were efficient sources of Zn for pea beans when mixed with a soil ranging in pH from 7.3 to 7.7. They also concluded that chelated Zn was even more effective. Even in Spain, researchers have confirmed a relationship between the water-soluble Zn and plant uptake (Alvarez and Gonzales, 2006).

Slaton *et al* (2005) conducted extensive field research that looked at Zn nutrition in rice in a study that compared four granular Zn fertilizers of differing solubility over different application rates in a soil with pH ranging from 7.4 to 7.5 in Arkansas. They concluded that the Zn must be 40-50% water-soluble and applied at ~10 lbs. Zn/ac to correct Zn deficiency in the current crop as well as build soil test Zn. They also found that Zn fertilizer recommendations should be based on a standard product, such as water-soluble $ZnSO_4$, so that products with lower solubility can be adjusted for application and economics can be compared. Finally, it was found that granular $ZnSO_4$ and a 10% granular lignosulfonate fertilizer performed equally well when applied over a range of rates. This indicates that $ZnSO_4$ and Zn lignosulfonate have a 1:1 efficiency ratio when based on elemental Zn rates. Previous research by Wilson *et al* (1996) evaluated a manufacturer's recommendation to apply 1 pound of the 10% Zn lignosulfonate fertilizer (10 lbs. fertilizer/ac) and found a significant decrease in yields as compared to rice receiving recommended rates.

University extension services across the nation are also reporting that Zn fertilizers should be chosen on the basis of Zn water-solubility and overwhelmingly recommend $ZnSO_4$. The North Dakota State University's extension web-site (http://www.ag.ndsu.edu/pubs/plantsci/soilfert/sf882w.htm) recommends applying $ZnSO_4$ for corn, potatoes, flax and edible beans. They also make special mention that Zn humates and lignosulfonates are not significantly more available than $ZnSO_4$ and stress the importance of water-solubility when choosing a Zn fertilizer.

The chapter on Nutrient Management in Kansas State University's Corn Production Handbook (Lamond, 1994) recommends $ZnSO_4$ depending on the soil test. The Kansas publication also makes note of the added efficiency of ZnEDTA and other true chelates.

The Tri-State Fertilizer Recommendation for Corn, Soybeans, Wheat, and Alfalfa (Ext. Bull. E-2567, Nov. 2000), which covers Michigan, Indiana, and Ohio, recommends applying the inorganic sulfate form of micronutrients due to their high water solubility. They also recommend the use of the oxide form with the caveat of applying as a finely ground powder to overcome lower solubility. Synthetic chelates of Zn (ZnEDTA) are recommended due to their stability in the soil and efficacy in correcting Zn deficiencies and are recommended to apply at 1/5 the rate of Zn as $ZnSO_4$. Finally, natural organic complexes of micronutrients are listed as well and they are described as variable and less effective than synthetic chelates per unit of Zn. They recommend applying complexed Zn at the same rate as the inorganic sources.

Zinc Fertilizer Application Methods

Over the years, micronutrients, especially Zn, have been applied in many forms and by many methods including: broadcast applications to the soil then incorporation into the soil before planting, banding below and to the side of the seed before or at the time of planting, sidedressing after plant emergence, foliar applications to plants, and also directly treating seeds or plant seedling roots with Zn. From the "Correction of Deficiencies" chapter in the book <u>Micronutrients in Agriculture</u> (1972) Murphy and Walsh described methods of Zn application.

Broadcast application of both inorganic and organic sources of Zn to the soil is one method. One common practice is to apply granules or powders of $ZnSO_4$ or ZnO and incorporate it throughout the root zone in the soil before planting. Another common practice is to apply the Zn along with NPK starter fertilizers. Murphy and Walsh (1972) cited the research of Boehle and Lindsay (1969) when they said that applications with mixed fertilizers or N fertilizers may enhance Zn uptake. They also point out that surface applications of Zn are ineffective due to the immobility of Zn in the soil.

Boehle and Lindsay (1969) also found that banding the fertilizer to the side and below the seed in the soil, especially in the chelate form, is an effective method of Zn fertilization. Banding is also more effective in supplying Zn to the plant roots as indicated by about 1/5 to 1/3 lower application rates recommended Colorado State University (www.ext.colostate.edu /pubs/crops/00538.html), which recommends 10 lbs. Zn/ac broadcast or 2 lbs. Zn/ac banded. This is also supported by North Dakota State University's Extension (http://www.ag.ndsu.edu/pubs/plantsci/soilfert/sf882w.htm). However, sidedressing Zn after crop emergence is the least effective soil application method (Boehle and Lindsay, 1969).

Foliar applications of Zn have been met with mixed success and it is generally accepted that they should only be used as temporary and emergency treatments. McNall (1967) was cited as having done extensive research on foliar treatments of Zn. He found that foliar uptake of nutrients does occur but is no substitute for root uptake.

Directly treating plant seeds and seedling roots with powders or solutions of Zn has also been tried and has ultimately been found unsuccessful. Rasmussen and Bowan (1969) were cited as having attempted seed treating beans with Zn and finding that it would not support the plant beyond the 3-compound leaf stage. This was supported by by Giordanno and Mortvedt (1973) where they found that coating rice seeds with $ZnSO_4$ had the same efficacy as application of $ZnSO_4$ applied to the soil or through the water.

As described above, mixing Zn with NPK fertilizers may increase uptake. It is also an easy and convenient way to apply Zn. When applying as part of an NPK fertilizer, there are several ways to accomplish this. One is to mechanically mix the Zn powder or granules with the NPK granules. Another method is to incorporate the Zn with the NPK granule in the manufacturing process when all the materials are molten or pressure granulate it. Also, the Zn can be coated on the outside of the NPK fertilizer granule.

In the chapter "Preparation of Fertilizers Containing Micronutrients" in the book Micronutrients in Agriculture (1972) Silverberg *et al* compared the different methods of incorporating Zn with NPK fertilizers. When mixing or dry blending Zn with finished granular NPK granules, the problem of segregation presents itself in two ways states Silverberg *et al* (1972). First, the Zn may separate from the mixture during the pouring of the fertilizer for transport or storage if the particle sizes of the two fertilizers are different. If the sizes do differ, "coning" or the effect of particles rolling down the side of a slope such as a pile of fertilizer will occur. Second, since perfect particle size matches can never occur in reality and particle density may differ, coning may still happen in transport. During spreading particles of differing density will also segregate causing a discrepancy in concentration in the field. However, there have been several ways developed to prevent this.

Incorporating Zn into NPK granules during the manufacturing process is a practice commonly done when the fertilizer is in a slurry or solution form. Silvergberg *et al* (1972) reported that the temperature and the pH of the slurry or solution determine what Zn material can be incorporated since they can cause reactions to occur that affect the solubility of the Zn. The NPK carrier and when the Zn is added in the manufacturing process is also paramount when applying Zn, especially in ammoniated fertilizers.

Many studies have been done to determine the effectiveness of different Zn sources with different NPK carriers. According to Mortvedt and Giordano (1969a), Zn was most agronomically effective when applied alone as $ZnSO_4$, however when granulated with other fertilizers it was most available in a N or K fertilizer, but not in a P fertilizer. Also, they found that $ZnSO_4$ and ZnO were equally soluble when applied with ammonium polyphosphate. However, when applied with concentrated superphosphate or urea, $ZnSO_4$ outperformed the ZnO. Additionally, they confirmed that as the pH of the fertilizer increased the Zn availability decreased. Lastly, they found that ZnEDTA was the most efficient Zn fertilizer source, even when granulated.

Another Mortvedt and Giordano (1969b) experiment showed that the most effective carrier of either $ZnSO_4$ or ZnO in the test group was concentrated superphosphate followed by triammonium pyrophosphate, ammonium polyphosphate, and monoammonium phosphate.

In an earlier study, Mortvedt (1968) confirmed these results when he found that Zn uptake was much higher when fine $ZnSO_4$ was mixed alone into the soil than when either $ZnSO_4$ or ZnO were a part of an ammoniated superphosphate granule.

In 1966, Giordano and Mortvedt found that Zn availability to corn as related to Zn source and concentration that ZnO and $ZnSO_4$ performed equally when incorporated into granules. Furthermore, they showed that their Zn sources were more available when incorporated with ammonium nitrate or ammonium polyphosphate but not with concentrated superphosphate. More importantly they also found that the manufacturing process (incorporation into molten NPK fertilizer or pressure granulation) did not affect Zn availability.

Another study done by Allen and Terman (1966) found that concentrated superphosphate and ammonium nitrate were equal in Zn availability and better than monoammonium phosphate and ammonium polyphosphate as carriers for $ZnSO_4$. Furthermore, ammonium nitrate and monoammonium phosphate was not a good carrier for ZnO while concentrated superphosphate and ammonium polyphosphate actually increased ZnO availability.

Mortvedt and Giordano's 1967 study on crop response to liquid and granular ZnO fertilizers found that triammonium pyrophosphate and ammonium polyphosphate performed equally and outperformed both monoammonium phosphate and ammonium nitrate, which were equal to each other.

Finally, when considering when to add the Zn to ammoniated fertilizers during the manufacturing process, there may be advantages to adding it before or after ammoniation depending on Zn source. Ellis *et al* (1965) in Michigan found that ZnEDTA decreased in availability to navy beans when added after partial ammoniation. On the other hand, incorporating $ZnSO_4$ before ammoniation decreased Zn solubility (Jackson *et al*, 1962).

Coating NPK granules with Zn fertilizers has the advantage of avoiding segregation and uneven distribution of Zn granules in the field. Silverberg *et al* (1972) describes the process of coating granules with Zn. First, finely ground Zn is dry mixed with the NPK fertilizer. The addition of a binder initially in the mixing process promotes the binding of the powder to the granule. Some common binders include light oils, waxes, water and even ammonium polyphosphate solution.

There has been mixed evidence to suggest that coating has no advantages over incorporation into NPK fertilizers. The 1965 Ellis *et al* study on pea bean Zn fertilizers found no difference between coating or incorporating Zn into NPK fertilizers with ZnO and $ZnSO_4$. They found that highly soluble ZnEDTA did have an advantage to being coated rather than incorporated (Table 2). Giordanno and Mortvedt (1972) report that there should be no difference between coating or incorporating Zn into NPK granules if it is water-soluble. Tanner and Grant (1973) found that ZnO coated onto an NPK granule was more available than $ZnSO_4$ incorporated into NPK granules, which was more effective than ZnO incorporated into the same NPK granule. $ZnSO_4$ coated was not tested in this study.

Table 2. Yield and zinc concentration of navy beans as affected by Zn source and method of inclusion with a granular NPK fertilizer in Mighigan. (Ellis *et al*, 1965)

Zn source[a]	Method of inclusion	Yield ($mt\,ha^{-1}$)	Zn in plants ($mg\,kg^{-1}$)
–	–	12.3	20
$ZnSO_4$	Blended	16.6	40
$ZnSO_4$	Incorporated	16.4	31
$ZnSO_4$	Coated	17.0	34
ZnO	Incorporated	16.2	23
ZnO	Coated	16.7	26
L.S.D. (0.05)		1.7	3

a. Fertilizers banded at planting to supply 3 kg of Zn/ha.

Zinc fertilizers can be also be added to fluid fertilizers. Silverberg *et al* (1972) cited Ulmer (1967) and Stinson (1966) for their work in incorporating Zn into N solutions such as ammonia-ammonium nitrate solutions, ammonium nitrate-water solutions, urea-ammonium nitrate solutions, and aqueous ammonia. These solutions proved successful if stored at the correct temperature to preserve solubility. However, use of most of these solutions has been discontinued due to the potential use of ammonium nitrate as an explosive. Zinc has also been added to ortho- and polyphosphate solutions. The orthophosphate solutions actually reduced the solubility of Zn to almost zero due to the formation of insoluble metallic ammonium orthophosphates like $ZnNH_4PO_4$. On the other hand, Lehr (1972) reported that the liquid and solid polyphosphate solutions did not affect solubility of Zn as much and in some cases increases the solubility of some of the more insoluble Zn sources, such as ZnO.

Zinc solubility was also not affected when added to acidic superphosphates (Hignett, 1964) but was limited when added to ammoniated superphosphates (Mortvedt, 1968). Finally, liquid fertilizers outperformed granular fertilizers when mixed with the soil but not always when band applied to the soil (Mortvedt and Giordano, 1967). Synthetic chelates and natural complexes of Zn have also been applied in a liquid form. The chelated Zn in liquid solution has been met with success while there have been some trouble with complexed Zn forming precipitates in fertilizer solutions (Ruffin, 1969 and Burman, 1969).

Zinc can also be applied as suspensions as long as the particle size can pass through sprayer nozzles and there is sufficient agitation to prevent balling of the particles (Silverberg *et al*, 1972). There has been some research done on this by Hergert *et al* (1984) and they had mixed results. Chelated forms performed poorly due to early-season leaching but were the most available source at a calcareous site. However, there were no statistical differences between any Zn sources as indicated by yield and only slight differences indicated by uptake.

Important Considerations with Granules

An important consideration when applying Zn fertilizers as a component of a liquid or solid NPK fertilizer is the pH effect the fertilizer will have on the soil. Zinc is most available at lower pH (5-7) and this is supported by many studies done over the years. A 1962 study done by Jackson *et al* showed that fertilizers having a pH of 4.6 to 6.1 had a larger capacity for supplying Zn than those with a pH greater than 6.1.

Another important consideration is granule size. Two studies have shown that granule size plays an important role in the plant availability of Zn (Silverberg *et al*, 1972 and Gordano and Mortvedt, 1966). The size of the granule mostly influences spatial distribution throughout the soil. One study found that as Zn concentration and granule size decreased, the distribution of Zn increased in the soil making it more available to plant roots (Allen and Terman, 1966). However, the most important consideration is to match the size of the Zn granule to the size of the NPK granule it is being blended with to avoid segregation during handling and spreading.

Zinc Mobility and Residual Effects in the Soil

For Zn to be available to plants the roots must come in contact with soluble Zn forms in the soil. Most of the time, it is by chance that plant roots find Zn in the soil as Zn is not very mobile in the soil. Some research has been done comparing different Zn sources and their mobility in the soil and it was found that Zn has very limited mobility in the soil. One of the earliest studies done by Giordano and Mortvedt (1966) found that the movement of Zn in soil from a granule site was limited to 1 cm for both ZnO and $ZnSO_4$ when applied with concentrated superphosphate. Also, increasing the Zn concentration did not influence the distance Zn moved away from the granule. A later study by Giordano and Mortvedt (1969) found that this may be due to the fact that soil reactions act on the Zn and convert it to less available forms rather quickly so soluble Zn does not stay soluble for long in the soil. Most recently, Gangloff *et al* (2006) conducted a leaching experiment that compared several different Zn sources and their mobility in the soil. They found that ZnEDTA, Zn lignosulfonate, and $ZnSO_4$ all were the most mobile, relatively, due to their solubility. Zn oxysulfate was less mobile but seemed to meet plant needs, while another, less soluble Zn oxysulfate and Zn sucrate were relatively immobile Zn sources.

Zinc availability over time was also studied by Shaver *et al*, (2006). They found that less soluble and mobile sources were not more available over time and would not provide additional residual Zn fertility in a time-released manner. However, North Dakota State University's Extension web-site (http://www.ag.ndsu.edu/pubs/plantsci/ soilfert/ sf882w.htm) states that an application of 10 lbs. Zn/ac as zinc sulfate either in a broadcast, or 1/3 of that rate as a band should correct Zn deficiency for 4 to 5 years. Several other researchers over the years have reported long lasting Zn fertility. Application method does not seem to have as much of an effect as application rate when it comes to residual effects of Zn fertilizers. Murphy and Walsh (1972) cited previous research when they report sufficient Zn from one application lasting from 2 to 10 years.

Conclusions

To summarize all of the above research and literature, the key to successful Zn fertility is water-solubility. The water solubility of the Zn source will determine how effective it will be in meeting plant needs (Amrani *et al*, 1999; Gangloff *et al*, 2002; Mortvedt, 1992; Liscanso *et al*, 2000; Slaton *et al*, 2005; and Westfall *et al*, 2005). Water solubility allows the Zn to move short distances in the soil and to be absorbed by the plant roots from the soil. It has been shown that ZnEDTA is the most effective source of Zn on the market. When ZnEDTA was used as a reference material on a plant uptake basis by Gangloff *et al* (2002), $ZnSO_4$ had a Relative Availability Coefficient (RAC) of 23%, followed by Zn lignosulfonate at 22%. All other sources are less effective with Zn oxysulfate compounds ranging from 0.5 to 12% and the organic complex Zn sucrate with an RAC of 5%. Therefore there is a significant difference between ZnEDTA and all other sources, no significant difference between $ZnSO_4$ and Zn lignosulfonate, and a significant difference between the Zn oxysulfates and Zn sucrate when compared to all the other sources in plant uptake (Gangloff *et al*, 2002). Generally speaking, a Zn source must be 40-50% water-soluble to be an efficient Zn fertilizer (Amrani *et al*, 1999; Liscanso *et al*, 2000; and Slanton *et al*, 2005). Finally, any claims of RAC different from the above would go against decades of research and the physical principles that are known to govern Zn availability in the soil and to the plant.

Concerning application methods, applying the above Zn sources alone as powders, granules, or in liquid solution or suspension to the soil in a broadcast or banded application and then incorporating them into the soil are effective means of Zn amendment. As a general rule, broadcast applications usually call for 10 lbs. Zn/ac and band application or application of chelate sources usually require only 1/3 to 1/5 of that

Zn rate, but always base application rates on soil test Zn levels (Ext. Bull. E-2567, Nov. 2000 and http://www.ag.ndsu.edu/pubs/plantsci/soilfert/sf882w.htm). Foliar and sidedressing methods are less effective (McNall, 1967) and seed as well as seedling treatments, which have seen little success (Rassmusen and Bowan, 1969 and Giordano and Mortvedt, 1973). It should be again emphasized that the only manners in which Zn fertilization rates can be reduced is through band applications or the application of a true chelate of Zn, such as ZnEDTA.

When applying Zn with an NPK fertilizer for the convenience, consider the carrier. Nitrogen fertilizers affect Zn availability less than P fertilizers (Mortvedt and Giordano, 1969a). When powders of Zn are applied as a coating on an NPK granule there is little evidence to suggest that they would perform any better than a granule of Zn (Ellis *et al*, 1965 and Giordano and Mortvedt, 1972) because it is a matter of spatial distribution in the soil and not difference in water-solubility. Additionally, the pH of the fertilizer carrier should be between 4.6 and 6.1 for highest availability (Jackson *et al*, 1962). Also, liquid fertilizers have been shown to outperform solid carriers (Mortvedt and Giordano, 1967). If a solid carrier is used, ensure that the granule size is matched to the size of the NPK granule it will be applied with to avoid segregation during handling and application (Silverberg *et al*, 1972). Finally, consider the limited mobility of Zn in the soil (Giordano and Mortvedt, 1966; Giordano and Mortvedt, 1969; and Gangloff *et al*, 2006) and ensure that it is incorporated into the root zone for most efficient uptake by the plant.

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