Zinc as a nutrient for agricultural crops in southern Australia

Scope

This review of the literature focuses on the function, importance and management of zinc (Zn) for wheat production in dryland cropping systems of south-eastern Australia. The review draws on a selection of cornerstone journal articles and book chapters that provide foundation information about role of and importance of Zn for wheat production. Information is sourced from the international literature and, where available, literature that provides specific Southern Regional content. The selected research and extension literature focuses at the regional level but is underpinned by the basic universal principles of Zn nutrition provided by the cornerstone journal articles and texts. Region-specific literature may be in the form of conference papers, fact sheets, technical reports or decision support systems (DSS).

These information sources are selected to assist advisers and growers to improve their understanding of N to provide the basis for improved decision making for managing Zn nutrition.

Outcome

This literature review is a guide that aims to enable advisers and growers to make better decisions about Zn management including whether Zn will be adequate or additional quantities of Zn need to be applied, and if so, where, when, in what form and at what rate. The review summarises the function, importance and use of Zn by plants in dryland cropping systems and provides a bibliography of reliable information sources. This literature review will be combined with reviews of other agronomic topics to provide growers and advisers with a carefully targeted source of information that will assist them to make more informed decisions about agronomic management.

Function of Zn in broad-acre grain crops

Nature of Zn in plants

Zinc is an essential micronutrient required for the growth of wheat (Grundon 1987) with crucial roles throughout the plant including in the transformation of carbohydrates, chlorophyll formation, the growth hormone auxin and enzymatic reactions (Sauchelli 1969). Zinc can mobilise to some extent within the plant with the degree of mobilisation dependent depends on Zn supply (Longnecker and Robson 1993). Symptoms of Zn deficiency commence on the middle leaves of the wheat shoot with pale green to brown stripes evident along the leaf. These symptoms extend to other leaves if the deficiency is persistent. Severe deficiency results in

stunted plants, reduced numbers of tillers and tillers without heads (Grundon 1987, Wurst *et al* 2010).

Nature of Zn in soil

Soil Zn is in several forms which are not all equality available to wheat; water soluble form Zn^{2+} (measured in parts per billion), adsorbed and exchangeable Zn, and insoluble Zn (Lindsay 1972, Broadley et al 2007). As Zn is taken up by plants, Zn becomes available from less labile forms. The relationships between the various forms of Zn and how their interaction is related to other chemical factors is reviewed by Barrow (1993).

Nature of Zn in soil

Plant roots take up Zn from soil solution as water soluble Zn^{2+} sourced from soil or fertiliser. The uptake of Zn from the soil and into the plant (Lindsay 1972) depends on:

- movement of the nutrient via mass flow or diffusion (from the soil to the root)
- the chemical availability of the nutrient (concentration, form and capacity to replenish Zn in soil solution from labile solid-state Zn)
- growth of roots through the soil (root interception)
- active and passive uptake of the nutrient at the root surface itself

Importance of Zn in south-eastern Australia

Most Australian soils under crop production are inherently low in most micronutrients including Zn. This includes acidic and alkaline soils, be they sands or clays. This is attributed to Australian soils arising from highly weathered parent material with low micronutrient nutrient status, including shell grit (Holloway *et al* 2008). Zn deficiency in wheat was initially recognised in Australia in the 1940's on the calcareous sandy soils of Western Australia (Riley *et al* 1992). Zinc deficiency in wheat is also evident as an issue in south-eastern Australia with 20% of wheat crops analysed by the South Australian Soil and Plant Analysis Service between 1995 and 1999 showing at least marginal deficiency in Zn (McDonald *et al* 2001). A similar survey of Victorian soils submitted to a commercial soil testing laboratory in 2011 shows Zn deficiency (< 0.5 mg/kg) present in 22% of Wimmera soils, 37% of Western District soils and 61% of Mallee soils (Norton *et al* 2012).

Local tools available to help Zn fertiliser decision making

Difficulties in interpreting soil test results leads to preference for plant testing as a quantitative diagnostic tool (BCG 2009). Alternatively, Norton et al (2012) advocate a subjective assessment of Zn availability by considering relevant soil factors; soil pH, soil moisture, organic matter, P content, soil texture and soil compaction. The overall message from GRDC in economically difficult conditions (2008, 2011) is to apply zinc to crops based on immediate need rather than use a program designed to build or replace nutrients. No specific timing for zinc application is recommended and no

agronomic preference is given for the thee application methods; seed dressing, soil fertiliser or foliar fertiliser. For applications to soil, Holloway (2006) states that best practice for calcareous soils in South Australia is to apply Zn and other elements in liquid rather than granular form.

The amount of major nutrients required for a crop is given in terms of kilogram required for a target grain yield but the equivalent for trace elements is not provided (GRDC 2011). Based on concentrations of zinc in wheat grain (23 +/- 7.3 mg/kg) grown as part of the National Variety Trials in 2008 and 2009 (Norton et al 2012) the amount of Zn removed is 47 – 91g for every 3 tonnes of grain/ha. The amount of zinc in the whole shoot of a non-deficient wheat plant at flowering is 17-51 mg/kg (Reuter et al 1997b). This is equivalent to 85 – 255g for a crop with an above ground biomass of 5 t/ha. This whole plant requirement is well-matched to the recommended foliar application rate of 330 g Zn/ha used in South Australia in the 1990s (Oliver et al 1997). Recommended rates of foliar Zn for use in South Australia have not changed in the last 15 years with the current amount required to correct Zn deficiency deemed to be 250 – 350 g Zn/ha (Wilhelm 2011).

Application rates of Zn are higher when applied to soil that when applied to leaves. BCG (2009) notes that accepted practice in the Mallee and Wimmera regions is to apply 2 to 3 kg Zn/ha to soil every three or four years despite no local evidence that frequent applications are required. Information about the availability of residual fertiliser Zn from Western Australia suggests that less frequent Zn applications will suffice however their soils are more acidic (Bolland and Brennan 2006, Brennan and Bolland 2007). In South Australia where there is known Zn deficiency, Wilhelm (2011) suggests initially applying 2 kg Zn/ha with annual applications for maintenance of 1 kg Zn/ha for 3 to 10 years depending on soil type. Soil types affects the suggested frequency of Zn required to maintain adequate Zn with more frequent applications on calcareous soils or in higher rainfall areas and less frequent applications (7-10 years) in low rainfall environments.

Principals of better crop nutrition

The principles for effective fertiliser use are to select the right source of nutrients, applied as the right rate, and in the right place and at the right time. These four rights (4Rs) of nutrient stewardship indicate that these four factors are all interlocking and if one is altered, the whole approach should be reconsidered (Bruulsema et al 2012, Norton and Roberts 2012).

Right source

There are three different forms of Zn fertilisers used in wheat production; seed dressing, fertiliser applied to soil and foliar fertiliser. There are few direct agronomic comparisons of the efficiency of these three fertiliser types on grain yield production of Australian wheat. GRDC (2008) only discriminates between them in terms of their immediate costs and residual effect. Soil-based fertilisers are used as a long-term strategy to increase or maintain Zn availability whilst seed dressing and foliar applications only resolve the immediate deficiency.

Zinc fertiliser is mainly applied to the soil at seeding time as either liquid or solid zinc sulphate ($ZnSO_4$), as solid zinc oxide (ZnO) (Mortvedt and Gilkes 1993), or as a natural contaminant of superphosphate generated from rock phosphate (Riley *et al* 1992). A major difference between ZnO_4 and ZnO is their solubility in water and therefore their immediate availability to plants; ZnO_4 is water soluble whilst ZnO has a low solubility in water (Mortvedt and Gilkes 1993). Alternative soil amendments that are by-products of other industries, including biosolids and flyash, are available in particular regions however there agronomic values is yet to comprehensively assessed and may contain toxic quantities of other heavy metals (Cooper 2005, Spark and Swift 2008).

Comparing the effectiveness of different Zn fertiliser forms shows that liquid $ZnSO_4$ is more effective at producing the same grain yield than granular $ZnSO_4$ and the Zn impurities in superphosphate (Mortvedt and Gilkes 1993). This general finding matches results from alkaline soils on the Eyre Peninsula in South Australia (Bertrand et al 2006) where liquid fertiliser produced higher grain yields than powdered fertiliser. However, the role of liquid Zn in the Eyre Peninsula research cannot be separated from the role of P and N as the fertilisers were a mix of P, N and Zn (Holloway *et al* 2001).

Brennan and Bolland (2006a) show that soil pH effects the effectiveness of powdered Zn fertilisers with $ZnSO_4$ being superior to ZnO on alkaline soils and equivalent on acid soils. Overall, these results indicate that $ZnSO_4$, particularly in a liquid form is a more efficient source of Zn that other soil applied Zn fertilisers especially in alkaline soils. The principles demonstrated by the research presented are likely to be applicable in south-eastern Australia however no local field research is available that examines Zn alone or compares ZnO and $ZnSO_4$.

Foliar application of Zn is an alternative to soil applied Zn fertiliser. Foliar application has the advantage of allowing Zn to be applied strategically based on seasonal progress and the occurrence of visual symptoms. Comparing the effect of foliar Zn and soil applied Zn on wheat grain yield shows no difference on an alkaline sandy loam on the Eyre Peninsula (Oliver *et al* 1997) and better yields with soil applied Zn on acid sands in Western Australia (Brennan 1991). The type of foliar Zn fertiliser, $ZnSO_4$ or zinc chelate, that was most effective for the wheat grown on sands was dependent on timing of application (Brennan 1991).

Foliar Zn fertiliser is applied to wheat in south-eastern Australia to reduce the impact of yellow leaf spot (*Pyenophora tritici-repentis*) however there is no evidence in referreed literature that this is an effective treatment for crop disease in wheat.

Right place

Logistically, placement of soil-applied fertilisers can be shallow or at depth. Ma (2009) reviewed the effectiveness of deep placement of fertilisers in Mediterranean environments, including south-eastern Australia. Deep placement of fertiliser generally means applying fertiliser at least 30mm below the seed. Placement of fertilisers containing elements with low mobility, including P and Zn, improves grain yields in environments where the top soil is prone to drying out and subsequently nutrients are immobilised (Lindsay 1972, Ma *et al* 2009). These environments include the sandy soils of Eyre Peninsula and low rainfall environments (Wilhelm 2005).

Australian research specifically examining the benefits of placing Zn at depth is rare (Bolland and Brennan 2006).

Right time

Wheat needs Zn to be available throughout the life of the plant (Longnecker and Robson 1993). Thus Zn must be supplied at seeding in soils deficient in Zn. The agronomic advantage of applying Zn at depth in soil prone to drying means that in practice Zn fertiliser must be applied before or during seeding in those environments. Similarly, the yield advantage of applying liquid fertiliser to calcareous and alkaline soils means that application must occur before or during seeding.

The timing of application for foliar Zn fertilisers is operationally more flexible than solid fertiliser. However, for yield responses, timing must occur early in crop growth if plants are deficient in Zn and are not to suffer a yield penalty (Brennan 1991). The most effective form of Zn in foliar applications varies with the timing of the application. Zinc chelate is more effective at increasing grain yield than $ZnSO_4$ when applied at 4 leaf stage (growth stage (GS) 14 according to Zadoks et al (1974). Both forms of foliar Zn are equally effective when applied later at mid-tillering (GS22-24).

Right amount

There are three general approaches to determining whether a nutrient needs to be applied soil testing, historical records plant testing.

Soil testing

Soil testing in a pre-emptive indicator for the amount of major nutrients (nitrogen (N), phosphorus (P) and potassium (K)) available to a planned crop. Soil samples are tested for Zn as a cheap adjunct to testing for major elements. Placement of soil-sampling points influences soil test results with higher Zn values occurring if all samples are taken on existing rows rather than between rows (Bolland and Brennan 2006b). Sampling randomly both in and between rows provides an overall Zn value for the sample area. Soil testing of the top 10cm layer is promoted for the major cropping soils in Australia as being relevant for making decisions about immobile plant nutrients such as P (GRDC 2009). Testing only the 0-10cm soil layer is also appropriate for Zn as most Zn in soil occurs in that soil layer and Zn as fertiliser remains in the vicinity of placement even in high rainfall conditions (>1000 mm/year) (Adcock et al 2007, Brennan and McGrath 1988).

Soil testing by DPTA-Zn

Extractable Zn is commonly measured in cropped soils (0-10cm layer) by extraction with DTPA as described in Method 12A1 by Rayment and Higginson (1992). The principle behind the DTPA extraction technique is that DPTA extracts solubilised and solid phase Zn from the soil similar to the extraction expected by plants. Given availability of Zn in soil is reduced as soil pH increases (Lindsay 1972), pH of the solution is standardised at pH7.3 for the extraction. Critical Zn values relevant to wheat for extractable Zn vary with soil type (Armour and Brennan 1999) and not all soil types have been calibrated for the extraction. This limits interpretation of test results with some soils being unresponsive to Zn although they are deemed to be Zn deficient (Oliver *et al* 1997). Critical Zn values by DPTA extraction for soil growing

wheat are 0.12 – 0.27 mg/kg for sandy soils in Western Australia and 0.8 mg/kg for red brown earths, clays and loams on the Eyre Peninsula and Mallee of South Australia (Armour and Brennan 1999).

A less commonly used method extracts Zn using EDTA (Method 12B1 in Rayment and Higginson 1992). However, soil calibrations for this method have not been pursued and subsequently are rare (Armour and Brennan 1999).

Historical records

Absence of Zn applications over many years (>10 years in sand over clay) may indicate a requirement for Zn fertiliser (Brennan and Bolland 2006a). Zn application through fertiliser is virtually omitted when high analysis fertilisers such as mono-ammonium phosphate (MAP) and di-ammonium phosphate (DAP) are used exclusively rather than fertilisers such as superphosphate that contain Zn impurities (Brennan 1991) that are sufficient for wheat production in Western Australia sands (Riley *et al* 1992). A history of symptoms of Zn deficiency in past crops does not always indicate that applying Zn fertiliser to the current crop will lead to an improvement in grain yield (Oliver et al 1997). This finding by Oliver *et al* (1997) for Zn applied to wheat grown on Eyre Peninsula supports Norton's *et al* (2012) exclusion of past Zn deficiencies in crop as an assessment criteria for determining if Zn fertiliser is warranted on a crop.

Crop testing

Zinc can be taken up by plants through the leaves (Haslett *et al* 2001). Therefore limited calibrations for soil Zn coupled with the technical possibility of foliar application of Zn makes tissue testing viable for diagnosing and correcting Zn deficiencies as the plant grows. Zinc is a trace element thus plant samples must be taken with care to avoid contamination with Zn from other sources such as soil or cutting tools (Reuter *et al* 1997a). Testing of the youngest emerged blade at GS23-30 for Zn may show that Zn concentration is below the range deemed minimal (16 to 20 mg/kg) by Reuter *et al* (1997b).

Other factors affecting availability of Zn to crops

Residual value

Zinc is largely immobile in soil and only moves short distances from the point of placement. In soil columns, Zn leaches less than 3cm down calcareous silty clay (Jurinka and Thorne 1955). In the field, Zn leached up to 6cm below the point of application in acidic sandy soils in Western Australia after heavy rains (Brennan and McGrath 1988). In contrast, Zn fertiliser moved up to 45cm into a sandy soil profile under young trees (Barrows et al 1960) These differences in movement support the inclusion of soil texture in subjective assessment for Zn availability (Norton et al 2012).

Zinc fertiliser applied to soil has a residual effect on crop growth for several years depending on crop and soil type. Lindsay (1972) concluded after reviewing the literature, that Zn fertilisers applied to soil have a residual effect for two to eight

years after application. The residual effect of Zn fertiliser on acidic sandy soil in Western Australia is estimated to be about 23 years for a single application at 0.5kg Zn/ha and about 40 years for a single application at 1 kg Zn/ha (Brennan and Bolland 2007). These timeframes cannot be extrapolated to the alkaline soils of south-eastern Australia due in part to the difference in pH.

Soil water

Soil moisture affects the availability of Zn to plants because most movement of Zn in the soil is by diffusion (Lindsay 1972). Thus uptake of Zn by plants is reduced under drier conditions as the diffusion rate is slowed. Dry soil also restricts root growth and thus the ability of the plant to seek out Zn in the soil, be it soil Zn or fertiliser Zn (Marschner 1993).

Soil pH

Soil pH is critical to the solubility of Zn^{2+} and the buffering capacity of the soil (Dang et al 1994, Lindsay 1972). Solubility of Zn^{2+} decreases as soil pH increases. This explains why critical soil Zn value derived for one soil cannot be readily extrapolated to another soil. Reduced solubility of Zn^{2} also helps explain why Zn deficiency is common in crops grown on the alkaline soils of the South Australia and north-western Victoria (McDonald et al 2001). Liming acid soils induces Zn deficiency in wheat on some acid soils in Western Australia (Brennan et al 2005).

In practical terms, alkaline soils may have the same extractable DTPA Zn value as acid soils yet show Zn deficiency in crop (Lindsay 1972). Dang et al (1993) found that Zn as measured by DTPA extraction was relatively poor at explaining variation in wheat yields (26%) compared to Zn buffering capacity which accounted for up to 62% of the variation. Despite the importance of Zn buffering capacity to Zn2+ solubility, this literature search found no equations to adjust extractable DPTA Zn as is available for soil P (Moody 2007).

Soil physicochemical constraints

Physiochemical constraints to crop growth are identified in several studies in south-eastern Australia and are summarised by Adcock *et al* (2007) as boron toxicity, carbonate, aluminate, salinity, sodicity and alkalinity. Alkalinity is the main physicochemical constraint to that directly reduces Zn uptake due to the dependence of Zn solubility on pH. Other physiochemical constraints that reduce root growth through the soil reduce access to soil Zn and will therefore reduce the availability of soil Zn to the plant (Lindsay 1972).

Effect of other nutrients on response to Zn

Plant roots must actively grow into soil that contains Zn fertiliser to enable Zn uptake. This requirement means that the limited availability of the major nutrients N and P that restricts root growth also restricts Zn uptake. Conversely, crops exhibit a Zn deficiency due to nutrient dilution when Zn availability is marginal and P and N are adequate (Loneragan and Webb 1993). Uptake of Zn from soil also effects uptake of other micronutrients in wheat and subsequent crop growth. Adequate Zn in soil coupled with inadequate copper (Cu) leads to Cu deficiency in wheat due to

competition between the two elements. Interactions between Zn and boron, manganese, iron and cobalt is also demonstrated overseas however they are unlikely to apply to the wheat production areas of south-eastern Australia given local climatic and soil conditions (Loneragan and Webb 1993).

Genetics for Zn efficiency

There is sufficient genetic variation in Zn uptake efficiency of wheat cultivars for the trait to be selected for in breeding programs (Graham and Rengel 1993, Genc and McDonald 2004). McDonald et al (2001) showed the Zn efficiency of 13 wheat cultivars ranged from 77% - 96% when grown in the Victorian Mallee (Birchip). Severity of visual symptoms of Zn deficiency is related to the plants Zn efficiency in low Zn soils with less efficient cultivars showing more severe symptoms than more efficiency cultivars (Genc and McDonald 2004).

Zn through mycorrhizae

Arbuscular mycorrhizae (AM) provides a source of nutrients to some crops such as sorghum. Wheat can be colonised by (AM), however, the crop is unresponsive to AM in terms of P or Zn uptake and grain yield (Ryan *et al* 2002, Ryan and Angus 2003).

Resources

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