Title: A review of management of micronutrients in cereal crops within the medium-low rainfall Northern Agricultural region of Western Australia

This literature review has been conducted by the Liebe Group with support from James Easton, CSBP and Richard Bell, Murdoch University through the GRDC investment "Benefits of foliar micronutrients on cereals in a low rainfall zone environment".

Scope

This review of literature focuses on the role, importance and management of micronutrients for wheat production in dryland cropping systems of the medium-low rainfall Northern Agricultural Region (NAR) of Western Australia. From this, the knowledge gap and therefore the research, development and extension (R,D&E) opportunities which exist for the further education and improvement of farming systems in the NAR will be determined. Conference proceedings, fact sheets, technical reports and decision support 'rules of thumb' were addressed in this review, to assess the appropriateness of agronomic decision support that is currently available to growers.

The literature review aims to identify the management of specific micronutrient deficiencies copper (Cu), zinc (Zn) and manganese (Mn), using plant sampling as the focus for understanding the extent of the issue being explored. Furthermore, the review will aid in the development of the research question being addressed by the GRDC investment, *Benefits of foliar micronutrients on cereals in a low rainfall zone*. A review of the function of each nutrient will provide the background understanding to nutrient deficiencies that exist within the ancient south-Western Australian agricultural landscape, along with investigation into the current grower standard practice for the management of micronutrient deficiencies.

Molybdenum is also a micronutrient of significant importance however, will not be explored in this review as it is less amenable to accurately measure in plant samples and therefore not as easily ameliorated by in season foliar treatment.

Background

Australia's ancient and eroded agricultural landscape has a predominance of soil profiles with exceptionally low fertility (Holloway, Graham, & Stacey, 2008). It has been highlighted by Holloway et al 2008, that Western Australia's agricultural soils were once the largest continuous area of naturally Zn deficient soil in the world. Such deficiencies of micronutrients in ancient soil types once posed critical production limitations to both mixed enterprise and broad acre cropping farmers throughout Western Australia. Large areas of farm land were treated with micronutrient fertilisers in the 1950-70's and in the following decades, supply of these micronutrients to crops was considered adequate.

However, with the adoption of more intensive crop rotations and the quest for higher yields, it is now becoming evident that areas of land, once not known for micronutrient deficiencies, are displaying symptoms of stress (Alloway, 2008). Nutrient management research and development in Western Australia, as in other parts of the world, has focused largely around macronutrients nitrogen (N), phosphorous (P) and potassium (K) due to the greater demand from crops for such nutrients (Bell & Dell, 2008). The advent of Variable Rate Technology (VRT) has allowed landowners to be more prescriptive in the way they manage their macro-nutrients and extensive research has supported this aspect of on-farm decision making. Micronutrients, conversely, are often not considered as a widespread limiting factor to crop performance (Easton, Understanding nutrient priorities and fertiliser decision making, 2018). Where micronutrients *are* considered to be a limiting factor to crop production, growers may be recommended to apply a foliar product to ameliorate the deficiency but this application needs to be based on sound agronomic advice about adequate rates and ideal crop stage. Source, rate and timing of micronutrient application may be investigated throughout this review to understand the impact such interactions have on crop health.

The micronutrient requirements for normal crop growth are small (Bell & Dell, 2008). Due to the disparity in crop requirements for macro and micro-nutrients, research priorities for micronutrients have not been of critical focus until the last two decades. Much of the research, conducted by Bolland and Brennan, that does extensively cover micronutrient management over the past two decades has been conducted in the high rainfall zones of the south Western Australian Wheatbelt; from Esperance to Bremer Bay in the south, and the medium to high rainfall areas pushing west through Calingiri, New Norcia, Dandaragan and Badgingarra. It is therefore of critical importance to the growers of the NAR, where rainfall, soil type and management practices differ, to investigate micronutrient requirements in greater detail. The lack of locally validated research data in the NAR raises the need to gain a better understanding of the potential scale and impact of micronutrient deficiencies in the region. Historical research and development activities provide a sound background of the potential impact on crop growth from micronutrient deficiencies; however recommendations have not been tested for their relevance to local conditions in the NAR.

Progressive increases in crop yields through improved varieties and agronomic advances are common in many farming systems, and in the past have seen immense and rapid economic gains (Bell & Dell, 2008). However, there are implications from the on-going demand for crops that yield higher, rotations that are more intensive and through expansion on to marginal land where nutrition is limited (Bell & Dell, 2008). Decline in growing season rainfall in the medium to low rainfall environment of the NAR has raised a growing concern around micronutrient management to maximise yield potential. The increased prevalence of deficiencies identified through paddock observation, raises the question about why these deficiencies are emerging where they did not previously limit crop growth and, what strategies or practices might be needed to manage these deficiencies in the future.

There are eight micronutrients essential for adequate plant growth; boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), nickel (Ni) and, zinc (Zn). Crops require a balance of appropriate nutrients in a pre-determined ratio dependent on the life cycle, environment and genotypic characteristics that influence a plant's maximum genetic potential (Karnataka, 2011). When the supply of one or more of these nutrients is inadequate; yield and quality of the crop will be impaired (Alloway, 2008).

It is important that both the macro and micronutrient requirements of crops are met, if they are to yield satisfactorily and produce a product (grain or fruit) that is of acceptable quality (Alloway, 2008). It is therefore important that soils and/or crops be monitored and analysed to ensure that the available micronutrient concentrations are within optimum range and meet the demands of the crop (Alloway, 2008). Too much nutrient supply creates a toxicity and too little causes deficiency; both having a negative impact on yield and quality.

Micronutrient demand in wheat

Crop production results in the removal of nutrients from the soil. Fertilisers are applied to maintain long term productivity, profitability and sustainability of the cropping system. Soil and plant testing is used to identify the occurrence of nutrient deficiencies and/or toxicities (Anderson, Harries, & Dolling, 2014) and aid the decision making process by growers, to manage nutrient removal according to grower best practice. To understand this further the requirements of micronutrients by wheat crops are described by considering nutrient requirements and nutrient removal.

Nutrients are removed from soil via several pathways, two of those being grain and straw. Removal of micronutrients from wheat crops varies from one soil type to another, fertiliser inputs and seasonal conditions endured by the crop; an approximate removal of micronutrients from grain may be in the range of 2.7 – 5.6 g Cu/t, 17 – 35 g Zn/t and, 33 – 61 g Mn/tn (Easton, 2018). On average, micronutrient removal by straw is also significant; approximately 6 g Cu/t, 21 g Zn/t and 12 g Mn/t is removed by wheat straw annually (Sahota, 2015). In any case, the largest impact on crop requirement and availability of micronutrients will be related to historical applications, environmental conditions and soil reactions (Easton, 2018). Applications of micronutrients to soil will, in most cases, far exceed what is removed by the crop and not all nutrients are taken up by the actively growing plant; some will be transformed or fixed in the soil (Sahota, 2015) or remain available for following crops except during periods of drought.

The determination of what nutrient levels are considered adequate or critical in plant samples depends on two factors; crop growth stage and dilution factor (McAlpine, 2018). The interaction with other nutrients will influence whether a micronutrient is adequate or deficient in a plant sample (McAlpine, 2018).

Cumming Smith British Petroleum (CSBP), is a local Western Australian fertiliser manufacturer, has conducted many decades of research to establish the critical levels of all nutrients required by plants both in soil and plant tissue and drives the models that assist growers and advisors to diagnose soil and plant nutrient levels. From this research a rough guide for plant critical levels, at late tillering (Z37), for Cu, Zn and Mn, that will not induce symptoms of deficiency, are as follows; >3 mg Cu/kg , >14 mg Zn/kg and, >20 mg Mn/kg . Often what is seen in the field can vary from one micronutrient to another and its interaction with other nutrients. When a cereal crop shows visual symptoms of deficiency, a plant test will generally return a deficient result (Bell R. , 2018) and provide confirmation of correctly diagnosed symptoms. Often, our observation of deficiency may be inaccurately diagnosed or mistaken for other environmental stresses unless a plant sample is able to confirm the deficient nutrient. Not all deficient plants will display symptoms.

Zinc

The function of zinc (Zn) is critical to enzymatic processes that promote plant metabolism and is essential for the production of chlorophyll, carbohydrates (Brennan R. F., 2000) and the growth hormone auxin (Sauchelli, 1969). Zn deficiency in agricultural crops such as wheat, barley and oats has been widely reported throughout Western Australia (Brennan R. F., 2000). The distribution of Zn deficiency in western and southern Australia was widespread and originally occurred in several million hectares of calcareous and siliceous sands and loams, as well as acidic soils (Brennan R. F., 2000). The most extensive tract of Zn deficient soil was 8 million hectares in south-Western Australia (Brennan R.

F., 2000). However, since these deficiencies were recognised widespread programmes of Zn fertiliser addition have increased topsoil Zn levels and thought to have corrected most of the Zn deficiency in crops. The key question here is whether hidden Zn deficiency exists as an unrecognised constraint due to changes in crop rotations (more continuous cropping), climate variability (frequent topsoil drying in the growing season) or soil management (no-till and nutrient concentration near the soil surface; lime addition inducing Zn deficiency).

When Western Australia's agricultural region was cleared, Zn based fertilisers were applied due to deficiencies detected in those soils (Brennan, Bolland, & Bell, Increased risk of zinc deficiency in wheat on soils limed to correct soil acidity, 2005). Initial applications of Zn fertilisers had a long-lasting residual effect of approximately 10-15 years; therefore only infrequent re-application was needed (Brennan R. F., 2001). Rates once used were at least 150 kg/ha of zinc enriched superphosphate annually or applied at a zinc oxide with Di-Ammonium Phosphate (DAP) (Brennan R. F., 2001). Current applications of Zn, via granular compound, 1-2 kg Zn oxide/ha (approximately 70% Zn), depending on soil type, will correct any deficiencies. Foliar applications of Zn sulphate (approximately 23% Zn) in 50-100 L/ha of water may also be applied upon detection of Zn deficiency to reduce the extent of yield loss (Brennan R. F., 2000)

Zn is largely immobile in soil and only moves a small distance from where it is placed, depending on soil type and texture (Brennan & McGrath, 1988). Where Zn has been applied there is significant residual effectiveness therefore, Zn does not need to be applied every year (Brennan R. F., 2000). In more sandy acidic soils of Western Australia, heavy rains may leach Zn up to 6 cm below the point of placement (Brennan & McGrath, 1988). On neutral to acidic soils in NAR it is not known how long before the fertiliser Zn applied with DAP in previous years will remain fully effective before re-application is needed (Brennan R. F., 2001).

Tissue tests are particularly useful for the assessment of Zn status in wheat crops (Brennan R. F., 2000). Plant whole tops and youngest emerged blades (YEB's) containing less than 12 mg Zn/kg are considered deficient whilst whole top samples with 20 mg Zn/kg or greater would be considered normal. Visual symptoms may become apparent in the field when samples show zinc levels between 12-16 mg Zn/kg in whole tops (Brennan R. F., 2000).

Soil testing is also another reliable method for assessing zinc status before a crop is sown. Diethylene thiamine pent acetate (DTPA) soil extractable Zn has been a good predictor of wheat crop response in specific soils. However, the critical concentration varies among soil types and what is considered adequate zinc levels, varies markedly (Brennan R. F., 2000). For example, a fine textured alkaline soil will have considerably higher critical levels of required Zn compared to acidic sands (Brennan R. F., 2000). Soil pH, clay content and organic carbon percentage (OC%) influence the critical level of DTPA extractable zinc. For acidic sands that have a pH of 5, OC 1% and clay content of 3%, the critical level of zinc would be 0.15 mg Zn/kg while alkaline soils at pH 8 would be 0.21 mg Zn/kg; as clay content and alkalinity increase, so too does the critical value and therefore the crop requirement for Zn.

Symptoms of severe Zn deficiency are usually seen on young seedlings early in the growing season (Brennan R. F., 2000). Deficiency commences on the middle leaves of the wheat shoot with pale green to brown stripes (in severe cases) evident along the leaf. If symptoms persist, it extends to each new emerging leaf (Brennan R. F., 2000). Severe deficiency results in stunted plants, reduced numbers of tillers and tillers without properly formed heads (Grundon, 1987). Therefore, it can be said that the physiological disruption caused by Zn deficiency can greatly reduce yields in severe cases (Brennan R. F., 2000). Where there is adequate soil Zn and spring conditions are dry, warm and sunny, often plants recover naturally from early transient deficiencies (Brennan R. F., 2000).

Figure 1: Severe zinc deficiency in mature wheat plant. Source: Diagnosing zinc deficiency in wheat https://www.agric.wa.gov.au/mycrop/diagnosing-zinc-deficiency-wheat

The addition of lime to ameliorate soil acidity, which has become common practice across southern Western Australian broad acre agricultural region, has been observed to induce Zn deficiency on the south west's sandier soil types, reducing grain yields (Brennan, Bolland, & Bell, 2005). This is due to the reduced plant availability of Zn where a rise in soil pH has occurred in the localised soil surrounding plant roots.

To ameliorate Zn deficiency, there are a number of options available to growers; Zn in granular fertiliser, Zn seed dressing and Zn foliar sprays. Early application of Zn is critical to its effectiveness and economic return. Late foliar applications of Zn where environmental conditions are warm, dry and sunny often provide little additional benefit (Brennan R. F., 2000). The addition of granular fertilisers containing at least 400 mg Zn/kg is sufficient for maintaining adequate soil Zn levels (Brennan R. F., 2000), to ensure the longevity of Zn supply for subsequent crops.

Copper

Copper (Cu) plays a vital role in the structural and functional role of enzymes and plant processes such as photosynthesis. Where Cu is deficient in the plant, consequences may include the inhibition of this photosynthetic pathway and/or the disruption to the production of lignin for cell wall structure and pollen development (Bell & Dell, 2008). Physical symptoms may appear as distorted or curled leaves, little to no pollen production at anthesis and, in severe cases; white heads indicating pollen sterility resulting in restricted grain set (Brennan R. F., 2000). Marginal deficiency may decrease grain set even though no symptoms are visible until maturity. Where deficiency is observed, grain yield losses due to copper may be 20% (Brennan, R. F., 2000), even up to 80% where visual symptoms have not occurred (Easton, 2018).

Figure 2: Severe copper deficiency in wheat. Source: Diagnosing copper deficiency in wheat https://www.agric.wa.gov.au/mycrop/diagnosing-copper-deficiency-wheat

Liming, soil pH and availability of Cu: The adsorption of Cu by the soil surface increases with increasing soil pH (Brennan R. F., 2000). It may therefore be observed that the addition of lime would lower the availability of Cu to the plants however this has not always been observed (Brennan R. F., 2000).

Interaction with other nutrients: Cu deficiencies in the plant can be induced where Zn fertilisers are applied (Brennan R. F., 2000). This interaction only occurs if soil Cu levels are marginal. If soil Cu levels are adequate, Zn is unlikely to affect Cu uptake in the plant (Brennan R. F., 2000). Copper is variably mobile in plants (Hill, Robson, & Loneragan, 1978); under low N, Cu is remobilised (old to young leaves) but under adequate N it is immobile (Brennan R. F., 2000).

Understanding if and when a wheat crop requires Cu, can be assessed using on row sampling both soil and plant testing. Soil testing can give inaccurate results depending on how the soil test is conducted (Brennan R. F., 2000). Due to the immobility of micronutrients such as Cu, it has been said to get an accurate reading of soil critical levels of Cu, one must sample on the existing crop rows rather than between the rows (Bolland & Brennan, 2006) and for a representative sample of the overall nutrition, sampling both in row and between the row becomes common practice (Bolland & Brennan, 2006). To gauge a broader representative sample of soil Cu levels, sampling can be conducted at random between the row and in the row (Bolland & Brennan, 2006). A deficient soil sample, that has been assessed using ammonium oxalate to extract the copper, will return a critical Cu level of 0.3 mg/kg or less from 0-10 cm samples (Brennan R. F., 2000). Soil testing using DTPA has since been developed to accurately diagnose soil Cu requirements. The critical value that is used for such soil tests is 0.3 mg/kg, where trials conducted by fertiliser companies such as CSBP have found strong accuracy and correlation between soil results and that of plant tissue concentrations when diagnosing potential deficiencies (Easton, 2018). Due to the minute amounts of copper required by plants, 0.3 mg/kg is still said to be deficient, while 0.8 mg/kg or above is more than adequate (Brennan R. F., 2000).

Tissue testing is the most common way growers assess Cu deficiency in Western Australian wheat crops (Brennan & Bolland, 2006). Brennan (2000) suggests that analysis of the YEB's at 5-8 leaf crop stage provide the most accurate method of assessing Cu. Plants returning concentrations of 1.3 mg

Cu/kg or below are said to be marginal to severely deficient while plants with 2 mg Cu/kg or more are considered healthy.

The requirement of micronutrients such as Cu are so small, the recommended rate, which is less than 1.2 kg/ha (Easton, Understanding nutrient priorities and fertiliser decision making, 2018) , can often be difficult to achieve as a uniform application (Bell & Dell, 2008) using conventional granular fertilisers. The distribution of Cu through the soil is critical to its availability. Due to its immobile nature in the soil, wheat roots can only take up Cu if they are within close proximity to the Cu fertiliser granule. The effectiveness also depends on the number and position of the Cu particles per unit volume of soil (Brennan R. F., 2000). While modern fertiliser manufacturing technology has allowed nutrition suppliers to include micronutrients into their bulk granular products, often a foliar application of micronutrient will be more convenient to uniformly ameliorate deficiency (Bell & Dell, 2008). The successful use of foliar applied liquid fertilisers to correct Cu deficiencies makes plant testing a viable option for diagnosing and managing Cu deficiencies as the crop grows (Brennan R. , 2006).

Residual value of copper is long, with single applications of Cu on deficient soils remaining available and fully effective up to 23 years after the initial application (Brennan R. F., 2000). However, experiments conducted by Brennan (2006), Gartrell and Robson (1980) have indicated that the residual value does decline significantly, beyond 30 years and, freshly applied Cu was required to reach target yields achieved by the initial Cu application. The increased use of nitrogen fertilisers has also seen a decline in Cu availability due to nitrogen causing Cu to become immobile thus increasing Cu requirements of wheat crops in south-western Australia (Gartrell, 1981). Thus, where soil samples show adequate levels of Cu, but plant samples suggest deficiency, the plant concentrations of other nutrients and seasonal conditions must be considered before action is taken to ameliorate symptoms.

Manganese

On a broad acre scale in Western Australia's agricultural region, manganese (Mn) was the first deficiency to be identified (Brennan R. F., 2000). While the deficiency is widespread, it is often confined to irregular, yet well-defined small patches (Figure 3) (Brennan R. F., 2000) on well-draining neutral or calcareous soils. However other soil types can also be subject to Mn deficiencies particularly where heavy applications of lime have been used (Hawson, 2016).

Figure 3: Irregular manganese deficient patches in wheat. Source: diagnosing manganese deficiency in wheat https://www.agric.wa.gov.au/mycrop/diagnosing-manganese-deficiency-wheat

Manganese plays an important role in many metabolic processes and photosynthesis (Brennan R. F., 2000). In plants displaying deficiency, the micronutrient is relatively immobile and will not be translocated from older leaves into new growth. Wheat is intermediately susceptible to Mn deficiency with other crops such as oats, barley (Brennan R. F., 2000) and lupins being more susceptible (White, Robson, & Fisher, 1981). Mn deficiency in these crops has been reported regularly throughout the southern, central and eastern regions of the Western Australian wheatbelt (Brennan R. F., 2000), on coastal alkaline soils and water repellent soils (Scanlan & Brennan, 2017); however it has not yet been reported as a significant impact to wheat production through the northern fringe of the central wheatbelt and NAR.

In cereals, symptoms of Mn deficiency are displayed as pale yellow-green patches with irregular but clearly defined edges (Figure 4) (Brennan R. F., 2000). As the crop matures, these areas of leaf tissue become paler and will be susceptible to wilt and will eventually die back. Symptoms will appear in the older leaves before extending to newer growth (Brennan R. F., 2000). Where manganese deficiency issues may arise, often the deficiency will be exacerbated by dry soil and high soil pH (including heavily limed soils) (Scanlan & Brennan, 2017).

Figure 4: Pale irregular patches if manganese deficiency in old wheat leaves. Source: Manganese deficiency – Wheat. http://www.yara.com.au/crop-nutrition/crops/wheat/crop-nutrition/deficiencies/mg/13470-magnesium-deficiency---wheat/

There are many tools available to aid in the diagnosis of Mn deficiency; the most accurate being plant testing of whole tops and, to a lesser extent, grain analysis. As mentioned earlier, critical levels in plant tissue should be >20 mg/kg, less than this may provide an indication that Mn levels are marginal (Brennan R. F., 2000) for the requirements of that crop at the time of sampling. Below 10 g/kg would indicate with certainty, a deficiency. If sampling youngest emerged blades (YEB's) of wheat crops, 12 g/kg would suggest deficiency (Brennan R. F., 2000). It is recommended that a foliar application be sprayed in test strips across the paddock, to ascertain the benefits of a Mn application and to check the diagnosis from tissue analysis (Brennan R. F., 2000).

Measuring Mn concentration in grain can be a diagnostic tool for deficiencies (Brennan R. F., 2000). As the test is retrospective, it may be considered misleading due to the re-translocation of Mn when the plant matures from vegetative state to a reproductive state (Brennan R. F., 2000). Grain analysis is not widely used in Western Australia or Australia for diagnosis of Mn deficiency in wheat (Brennan R. F., 2000).

Soil testing is considered the least reliable method of measuring Mn due to the variability in soil Mn concentration over time and the influence of soil conditions (eg. soil moisture) (Brennan R. F., 2000). Soil testing is used as a rough guide with levels <2 mg/kg in 0-10 cm samples considered problematic (Brennan R. F., 2000).

Soil properties such as clay content, organic matter, pH and microbial activity heavily influence the availability of Mn to wheat plants (Brennan R. F., 2000). Where manganese fertilisers, such as manganese sulphate drilled with compound or superphosphate have been used (Brennan R. F., 2000), the residual value of these previous applications (if only applied as a once off) decreases over time relative to the effectiveness of freshly applied Mn (Brennan, Gartrell, & Adock, 2001). This residual value however does vary between soil type (Brennan, Gartrell, & Adock, 2001) and seasonal conditions (availability of soil moisture). For example, Mn applied to sandy soils will have a larger decrease in residual effectiveness compared to gravelly sands (Brennan, Gartrell, & Adock, 2001).

To ameliorate Mn deficiencies it has been recommended by agronomists to apply the micronutrient as compound form with other macro-nutrients whilst the alternatives are foliar sprays of various forms; sulphates, oxides, chelates and carbonates (Brennan R. F., 2000). Foliar sprays such as Mn sulphate are often very effective if applied early in the crops development and, before symptoms cause stunting (Brennan R. F., 2000). Foliar applications of products containing manganese sulphate are recommended to be sprayed at 4 kg/ha in 100 L/ha water or comparable amounts where spray-grade products such as mantrac pro® however; such products free of impurities are more costly (Brennan R. F., 2000) than alternative non-spray grade products.

Micronutrient source

Micronutrients are available in various sources which influence the way in which they are used and their availability to the crop. This presents an opportunity to further investigate the efficacy of the various micronutrient sources available to growers'.

There are several inorganic sources of micronutrients available for Cu, Zn and Mn. These inorganic sources include sulphates, chlorides, oxides, ethylenediaminetetraacetic acid (EDTA) chelates and carbonates, all of which have various levels of efficacy depending on how and when they are used.

Sulphates (SO_4) of Cu, Zn and Mn are the most commonly used sources of micronutrient and are readily available to the plant after application to soil or foliar treatments (Voss, 1998).

Chloride (Cl) sources are not as common but are available for Cu, Zn and Mn as liquids for use in liquid fertiliser banding.

Carbonate sources of micronutrients are less soluble than sulphates but both are prone to soil reactions where, in solution, their ionic charge alters however many liquid forms of the micronutrient Mn, is a carbonate (Easton, 2018).

Oxides of Cu, Zn and Mn are often used in the formulation of compound fertilisers that have micronutrients added but also exist as seed treatments and foliar applicable liquids. The availability of micronutrients in this form depends on their reaction with the localised soil properties, placement and reaction with other inorganic fertiliser nutrients (Voss, 1998).

EDTA Chelates are the most common source of *organic micronutrients* which exist in their elemental metallic base. Chelating agents such as EDTA are used to keep the micronutrients in solution and plant available particularly under alkaline soil pH conditions where the nutrients normally form insoluble compounds (Voss, 1998). Copper and Zn chelates are more effective than Mn chelates due to their high stability constant (are not displaced easily) (Easton, 2018). Other metals such as Fe, Cu and Zn displace Mn thus limiting the transport of Mn to the plant root (Easton, 2018). It has been shown that Mn chelates are less effective in soil applications compared to other sources of Mn (Walter, 1988). Chelated micronutrient sources, while more efficient than inorganic sources, are significantly more expensive than their inorganic substitutes (Voss, 1998).

Impact of prior R, D & E

Extensive research has been conducted over the past 90 years to determine the extent of micronutrient deficient soils both globally and on a local level across Australia. The first report of wheat yield responses to the application of Zn in Western Australia occurred in 1940-1941 on calcareous sandy soils (Holloway, Graham, & Stacey, 2008).

The ancient calcareous and acid sands of Western Australia give rise to a wealth of nutrient interactions; where two or more micronutrients or, micro and macronutrients are both agronomically and economically important (Holloway, Graham, & Stacey, 2008). Management of micronutrient deficiencies must therefore be timely and economic.

Diagnostic tools such as soil and plant testing aid in the detection of deficiencies and will often result in a recommendation or management strategy. The development of specifically calibrated measurements that allow us to accurately detect soil nutrient properties has its limitations; for example, copper test calibrations are time consuming and costly depending on the testing procedure adopted and the values that are considered critical under each procedure and for multiple soil types that exist in our agricultural landscape (Brennan & Bolland, 2006). By contrast, it has been found that critical tissue test values in plants (whole tops and YEB's) were unaffected by soil type (Brennan & Bolland, 2006). Therefore, tissue testing is likely to remain the most reliable and accurate method of diagnosing Cu and other micronutrient deficiencies for wheat, in south-west Western Australia and, for determining when and what rate of micronutrient should be applied (Brennan & Bolland, 2006). Anderson, Harries and Dolling (2014) conducted research which investigated the sustainability of south-western Australian cropping systems through the examination of the frequency of soil and tissue results below critical values and the return from such tests for the improvement of fertiliser decision making. What became evident from this research was that growers were effectively managing their fertiliser inputs, resulting in a low frequency of soil and tissue test values below critical level (Anderson, Harries, & Dolling, 2014). Where deficiencies are suspected or observed by growers in field, tissue testing remains a critical tool for diagnosis.

Bolland and Brennan (2006) conducted research investigating the requirements of P, Cu and Zn under modern no-till farming systems from Mullewa in the north, as far south as Mount Barker and Esperance in the south and Merredin in the east (Figure 5).

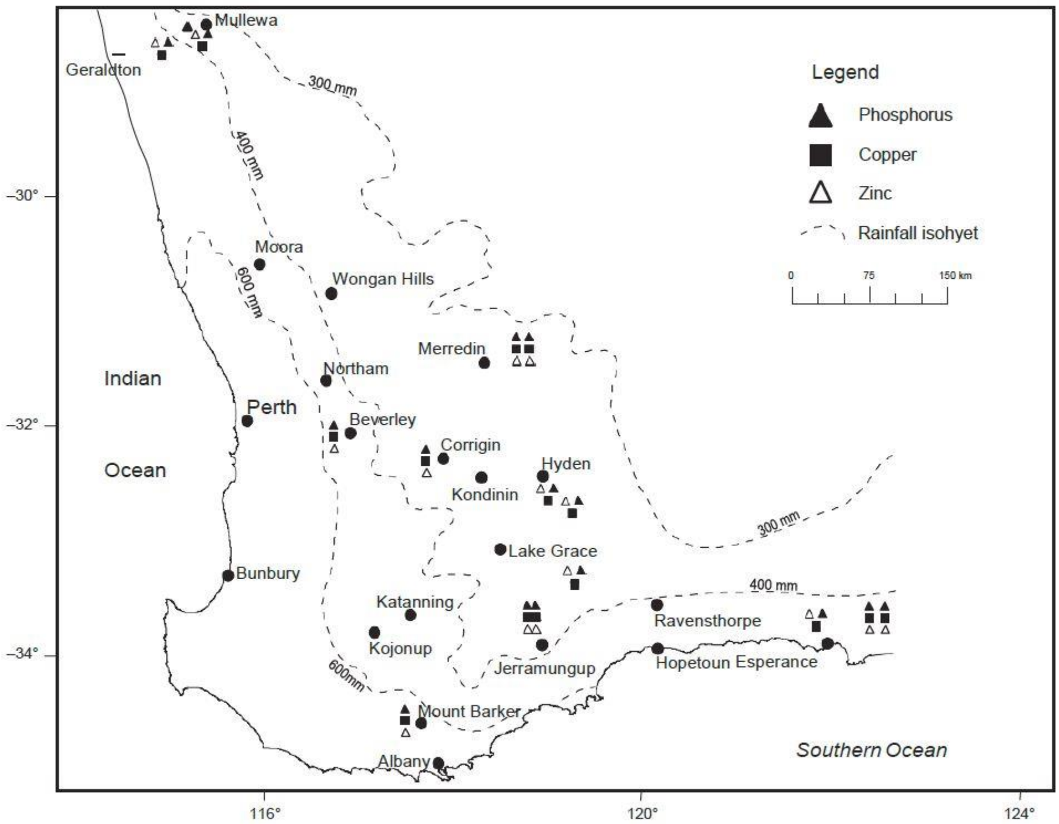

Figure 5: Map of south-western Australia indicating locations of phosphorus (▲), copper (■) and zinc (△) experiments **(Bolland & Brennan, 2006)**

Where no-till management practices had been adopted for seven years or greater, plant testing conducted at each of those sites (Figure 5) indicated marginal to deficient levels of soil immobile elements P, Cu and Zn (Bolland & Brennan, 2006).

Nutrients (P, Cu and Zn) were all commonly used in drilled fertilisers at seeding and, under a no-till farming system, were no longer mixed through the top 10 cm of soil, due to the stratification effect of no-till farming systems, in the years after application (Bolland & Brennan, 2006). The soil profile adjacent to the sown furrow became deficient of these nutrients (Bolland & Brennan, 2006) for exploring secondary roots of crops.

With no-till farming dominating south Western Australia's agricultural landscape, the trials conducted by Bolland and Brennan (2006) provided a sound understanding of nutrient movement and availability under these systems. However their extensive investigation of P, Cu and Zn in 46 experiments at 16 sites (Bolland & Brennan, 2006) was confined to areas within the medium to high rainfall zones (Figure 6), with the exception of sites at Merredin.

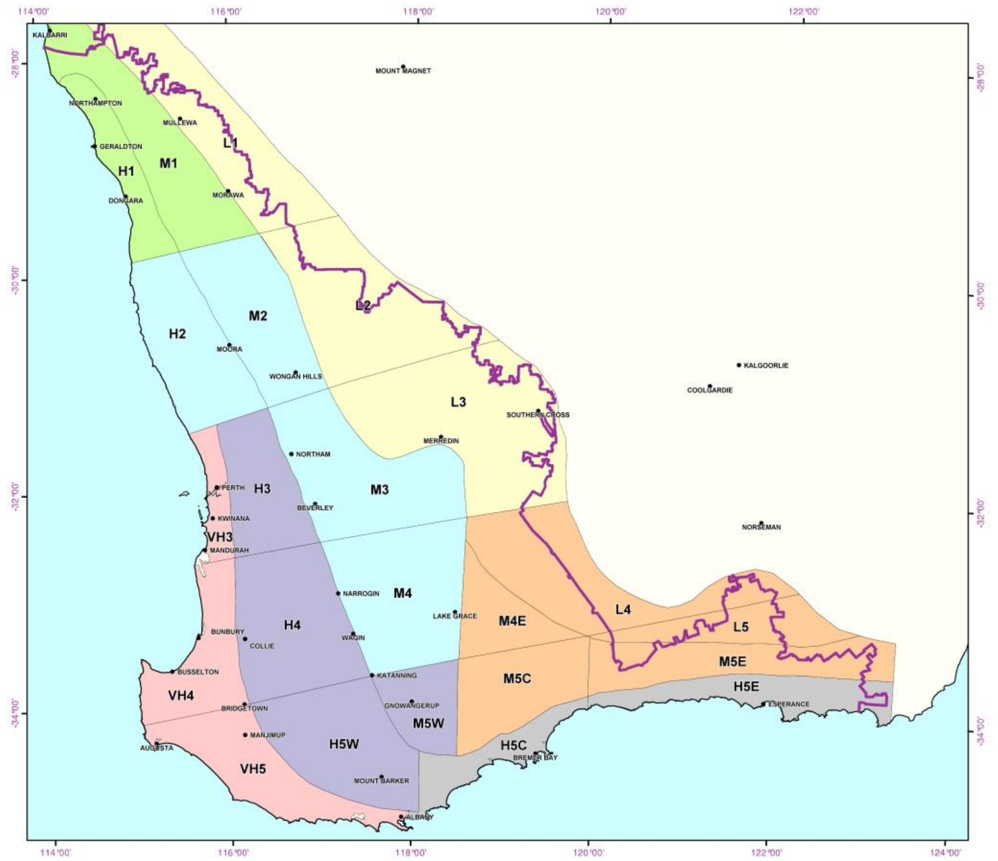

Figure 6: Geographical Rainfall and Crop Variety Testing (CVT) zones of Western Australia. Source: Geographic information services map (2016). https://researchlibrary.agric.wa.gov.au/gis_maps/1/

The scope of the project investigating the *benefits of foliar micronutrients on cereals in a low rainfall zone* aims to collect plant tissue data from across the NAR, which encompasses both the medium rainfall zone M2 to the west and the low rainfall areas of L2 in the east (Figure 6), where research has previously been limited.

In 2015 a report was compiled and published for the GRDC funded DAW00213 Focus Paddock Project. This project included a large scale survey of 184 paddocks (Figure 7) which were both soil and plant sampled for macro and micronutrients. The key findings from this report indicated that Cu deficiency was only found in 3% of the paddocks soil tested, whilst Zn was adequate in all samples. A further 28% of paddocks were found to have marginal soil Mn levels and it was therefore recommended to use plant sample analysis to determine plant Mn requirements, particularly where lupins were grown on sandier soil types and where soil had been ameliorated with lime (Harries, Anderson, & Nutt, 2015).

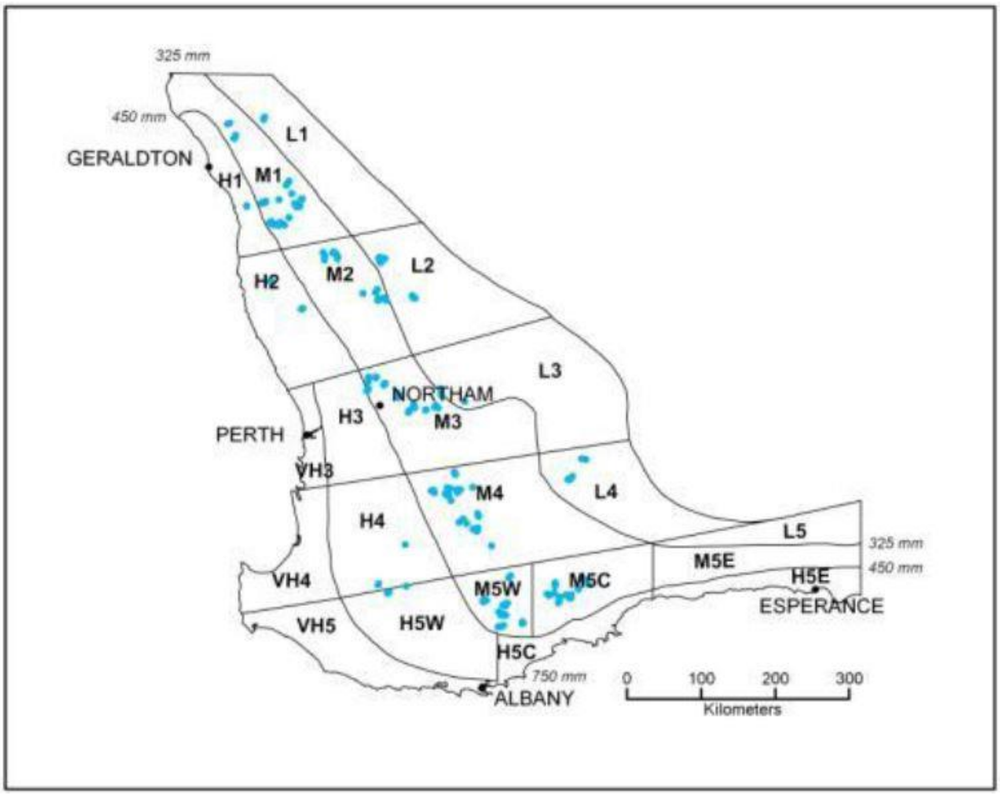

Figure 7: Paddock locations across south-western Australian cropping zones where the Focus Paddock plant and soil survey was undertaken, 2010-2014 **(Harries, Anderson, & Nutt, 2015)**

To confirm the micronutrient status of the soil, using plant testing as an indicator of nutrient uptake, marginal Cu levels were found in whole top samples collected in an average of 9% of paddocks planted to cereals in 2011 (Harries, Anderson, & Nutt, 2015). Nine percent of paddocks showed Zn concentration <20 mg/kg in cereal whole tops taken from 2010 to 2014, which is still considered sufficient. After five years of sampling, whole top samples indicated a 0% incidence of plants having a severely deficient level <11 mg/kg of Mn however this increased to 46% incidence of samples that were considered above critical levels with Mn levels between 11-100 mg/kg (Harries, Anderson, & Nutt, 2015).

Plant analysis from the Focus Paddock Project indicated that micronutrient deficiencies were more significant than soil analysis first suggested, and the growing concern about micronutrient status in plants continues. A Liebe Group survey conducted in 2018 indicated that 74% of growers across the Dalwallinu, Wongan Hills, Coorow, Perenjori, Carnamah and Moora Shires believed their crops suffer from micronutrient deficiencies. Forty-one percent of those surveyed indicated that Mn was their most limiting micronutrient, followed by Zn (25%) and Cu (10%). Most of these deficiencies were considered to exist on deep sandy earths and sandy duplex soil types. This level of concern for the management of crop nutrition has seen a resurgence of interest in the use of micronutrients in the past few years (Brennan, Easton, & Bell, 2017). Micronutrient deficiencies are being diagnosed early in the season, soon after emergence, where post-seeding drought occurs (Brennan, Easton, & Bell, 2017).

Various environmental and genetic variations are said to influence the expression of micronutrient deficiencies including positional availability related to minimum tillage seeding practices (Brennan, Easton, & Bell, 2017), and seasonal conditions including periods of prolonged drought after crop emergence.

With improved availability of micronutrient fertilisers, particularly in liquid form, alternative methods of micronutrient application were studied in depth in a four-year project conducted by Brennan, Easton and Bell (2017). The four-year study tested micronutrients banded as compound fertilisers, liquid banded at seeding and foliar applications of micronutrients Zn, Mn and Cu. Results from this study concluded that there was a significant response to Mn where it was applied as an early foliar spray (Figure 8). Late application (at booting) of Mn was ineffective (Brennan, Easton, & Bell, 2017). Both foliar and liquid banded applications of Cu, Mn and Zn were effective in correcting visible symptoms of deficiency, with a site at York recording significant yield responses to foliar and liquid banded Cu (Brennan, Easton, & Bell, 2017).

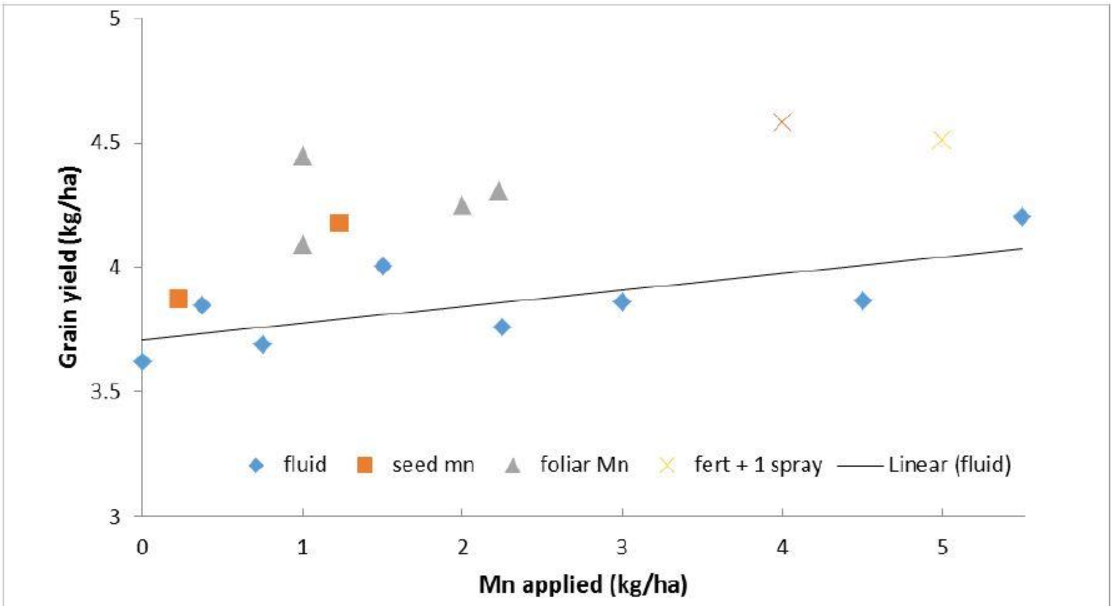

Figure 8: Grain yield of wheat in response to Mn Sources and rates at East Scaddan **(Brennan, Easton, & Bell, 2017)**

Applications of micronutrients via foliar application have also been supported by research conducted by CSBP in 1995, at a sand over clay site in the medium-low rainfall region of Wyalkatchem (Table 1). At this site, the addition of a foliar Cu spray with nitrogen, at Z30, resulted in a yield increase of 0.67 t/ha. Treatments where Cu was applied as an individual foliar spray also resulted in a 0.63 t/ha yield increase. These yield increases equated to a $120/ha boost in income at a $190/t grain price. Potential financial benefit of such applications at today's APW1 price of $313/t (Glencore Grain, 2018) would be over $197/t less the cost of product which is approximately $7/ha plus grower application costs. The plant analysis for the Wyalkatchem experiment indicated low levels of Cu. While plant levels were low, symptoms are often not visible unless deficiency is severe. The increased yield achieved by the foliar applications in this trial, illustrates the importance and value of plant testing (CSBP, 1995).

Table 1: Assessment of yield with and without foliar application of copper oxychloride at Wyalkatchem (CSBP, 1995)

Wyalkatchem, 1995 Sand over clay						**Yield** (t/ha)		**Protein** (%)	
	Treatment	**N**	**P**	**K**	**S**	**+ Cu**	**-Cu**	**+ Cu**	**-Cu**

1.	123 Agrich, 98 Urea, 100 Potash	60	14	50	15	**3.12**	2.49	9.1	10.4
2.	154 Super Phos, 100 Potash	0	14	50	18	2.45	2.45	8.4	8.8
3.	123 Agrich, 33 Urea, 100 Potash	30	14	50	15	2.97	2.43	8.9	9.1

*Not Recorded (NR). *Treatments where Cu was not applied have not been shown in this table.*

What is evident from the trial at Wyalkatchem is the positive response to Cu appears to be influenced by its interaction with other macronutrients; in particular, where there is adequate nitrogen all treatments which received a foliar Cu application yielded significantly higher however, in the absence of N, there was no additional yield benefit obtained from a foliar application, due to the N requirements limiting crop growth. Grain quality was adversely affected by the addition of Cu however this was due to the dilution effect that occurs when a crop yields higher and no additional nitrogen has been applied.

A 2012 trial conducted by CSBP on a gravelly sandy loam at a property near Calingiri, tested various Mn products as sulphates, chelates and carbonates, both banded as liquid, in compound and as foliar applications. These treatments were applied to a known responsive site however results concluded that Mn banded in the form of Mn sulphate in a compound fertiliser yielded significantly higher than all banded liquid products. Where foliar Mn was applied, two applications of a Mn sulphate at Z23 and Z30 were the most effective, with a significantly higher grain yield compared to a single application of Mn sulphate or Mn carbonate at Z23 (StrataSol®) (CSBP, 2012). Such results highlight the need for further research into the timing of foliar Mn fertilisers to improve crop yield, along with economic impact of such treatments.

Micronutrient source was also tested by Brennan and Bolland (2006) in a glasshouse pot trial where zinc sulphate ($ZnSO_4$) and zinc oxide (ZnO) were applied to both alkaline and acid soils. Both sources of Zn were effective on acid soil however; on alkaline soil, twice the amount of ZnO was required to produce the same yield as treatments with $ZnSO_4$ (Brennan & Bolland, 2006). Youngest emerged blades (50 day old shoots) were tested to assess tissue level of Zn after both treatments were applied. The critical concentration from these tissue tests was measured as the concentration required to produce 90% of maximum yield, which was approximately 13 mg Zn/kg, irrespective of source or soil (Brennan & Bolland, 2006). With various soil types and properties present throughout the low rainfall zone of the NAR, micronutrient source should also be important when considering what strategy to adopt when ameliorating deficiency in field.

Summary and future research opportunities

Evolving farming practices and the addition of lime to farming soils has led to growers questioning the availability and adequacy of micronutrients for crop production. Prior research into the scale and impact of micronutrient deficiencies across south-western Australia has provided the precedence to continue thorough and investigative research into the subject. The process which this project will adopt to identify gaps in understanding is supported by industry partners who have also identified the limited research and development in the area of foliar micronutrient management in the NAR.

Prior research gives confidence to the diagnostic tools and management practices available to growers throughout south-western Australia. On-farm soil sampling is relatively widely adopted to understand nutrient status and constraints to crop growth. Plant sampling on the contrary is a tool not as widely used by growers and hence both the data and understanding of the usefulness of this as a decision making tool is lacking. This ability to diagnose and ground-truth deficiencies that can either be symptomatic or asymptomatic through the use of plant testing, allows growers to make informed and timely fertiliser decisions that may improve their crops yield potential if managed with the correct product, at the correct rate and at the correct crop stage.

Whilst there has been considerable research conducted on micronutrients, in recent times, as previously highlighted, where conditions are favourable and soil levels are adequate, some deficiencies may only be transient. What is not clearly understood is the full impact undiagnosed deficiencies are having on crop yields and in turn the grower's production bottom line. With increasing frequency of prolonged drought periods post seeding to early emergence, growers in the medium to low rainfall areas of the NAR are seeking improved confidence in the diagnosis and economical treatment of micronutrient deficiencies through the use of plant testing.

Significant research has been undertaken to understand the impact and prevalence of micronutrient deficiencies in crops in Western Australia. Predominantly much of this research has been undertaken in southern and central Wheatbelt in the medium to high rainfall zones. It has been identified through this review that there exists a significant geographical gap in this research within the medium to low rainfall zone of the NAR.

Despite the belief by growers that there are micronutrient deficiencies in their crops, the question of the scale and impact of this on the NAR is still somewhat unknown. To establish a greater understanding of the scale and locations of potential micronutrient deficiencies this research project will undertake an extensive plant sampling survey of the Liebe Group region. The project being delivered by the Liebe Group, aims to address this knowledge gap through the adoption of specific process, with the aid of tools such as plant testing and with the guidance of nutrition specialists, equipped to identify and diagnose deficiencies throughout the medium-low rainfall zone of the NAR. Small scale on-farm trial work, using Cu, Zn and Mn foliar products of various sources, can be explored where micronutrient deficiencies are identified in the plant sampling process and, will further aid in growing awareness and adoption of tools and strategies to manage such deficiencies.

Active project engagement from participating growers endeavours to improve awareness of the scale of micronutrient impact and potential adoption of plant sampling as a tool for diagnosis of micronutrient deficiencies. The process which will be undertaken to successfully implement this project, will feed valuable information and data about the nutrition status of the NAR region directly back to growers, GRDC and industry partners, increasing the value of the services provided and allowing researchers to adequately assess the relevance of future research opportunities which align with regional concerns.

Based on the background research identified within this review it can be summarised that there remains a gap in micronutrient research of geographical relevance to the region. The scale and impact of micronutrient deficiencies within this region have not been fully understood through a plant sampling methodology. The establishment of a relevant data set for the region would aid in the identification of the presence of and economic impact of micronutrient deficiencies in cereal crops of the NAR.

Research opportunities that exist within the project;

- Measure of uptake and adoption of plant testing for the diagnosis of micronutrient deficiencies
- Scale and impact of micronutrient deficiency in the medium to low rainfall zone of the NAR through plant sampling and grower survey's which will be conducted across an extensive geographical area.
- Investigation into the cause of micronutrient deficiency at individual on-farm demonstration sites, including in-field trial work using foliar micronutrient products.
- Measure of efficacy of source, rate and timing of foliar applications of micronutrients Cu, Zn and Mn.
- Improve both production and economic return on investment from the application and therefore, the adoption of foliar micronutrient products.

Future research opportunities that exist for the medium to low rainfall zone of the NAR

- Herbicide interaction with efficacy of foliar micronutrients.
- Impact of strategic deep cultivation and re-distribution of micronutrients on soil and plant test levels.
- Economic benefit of granular versus foliar applied micronutrients on limed acid soils.
- Micronutrient management strategies for crops which experience prolonged post seeding drought.

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