

Trace Element disorders in South Australian Agriculture

The successful development of modern agricultural industries in most regions of South Australia could not have been achieved without the discovery and correction of trace element deficiencies in crops, pastures, horticultural tree and vegetable crops, plantation forests and livestock. Over the past eight decades, the low trace element status of many SA agricultural soils has been demonstrated repeatedly and often multiple deficiencies were identified. Their amelioration with trace element fertilisers (together with macronutrients, phosphorus (P), nitrogen (N), potassium (K) and/or sulphur (S)) led to:

- the development of large tracts of infertile land for agricultural production;
- spectacular increases in yields and the quality of harvested products; and
- marked improvements in livestock productivity, carrying capacity and the quality of livestock products.

The research which underpinned these remarkable gains in agricultural productivity often paralleled or preceded similar research undertaken elsewhere in Australia, notably in Western Australia. In some cases, the advances had international application, such as establishing the cause for and effective measures for preventing “coast disease” in sheep. It is also worth noting that the pioneering researchers had to confront considerable scientific challenges, since they lacked the modern analytical technologies that we take for granted today.

As Professors CM Donald and JA Prescott stated in 1975 at the Waite Institute Jubilee International Symposium on Trace Elements:

“No country has derived greater benefit from trace elements than Australia”.

Pioneering discoveries (1928 – 1960):

In 1928, Dr CS Piper (a chemist) and Geoffrey Samuel (a plant pathologist) from the Waite Institute reported the *first trace element disorder identified in Australia* - manganese (Mn) deficiency in oats grown adjacent to limestone roads (known locally as ‘roadside takeall’ or ‘grey speck disease’) at Penola and Mount Gambier. The authors noted that oats were more susceptible than wheat or barley. Sixty years later, an International Symposium on Mn was held at the Waite to commemorate this original discovery.

Four years later, RC Scott (Departmental Supervisor of Experimental Work) reported marked responses to drilled applications of manganese sulphate and superphosphate on barley crops grown on calcareous soils at Corny Point on southern Yorke Peninsula between 1928 and 1931.

Livestock nutrition:

Coast disease, a wasting disease in sheep grazing calcareous soils along coastal areas, was the first disorder tackled by livestock nutritionists. Investigations led by Dr

Hedley Marston of CSIR (later CSIRO) Division of Animal Health and Nutrition commenced in 1929 firstly on Kangaroo Island and later at Robe.

In 1935, Ted Lines of the Division administered oral supplements of purified cobalt (Co) to penned sheep transferred from Kangaroo Island (KI) that were affected by the wasting disorder. He obtained an immediate positive response. *This was a critical world first report on the essential requirement of Co in livestock*, that was later verified in the field at Robe and also at Denmark in WA.

In 1938, Dr Marston and colleagues at CSIR reported that acute coast disease in sheep on the farm of Mr Robert W Dawson at Robe *was caused by dual deficiencies of copper (Cu) and Co*. Mr Dawson and his family generously provided land for Divisional research that continued from 1935 until 1976. The soil was highly calcareous (66 % lime). The Robe community commemorated the major research achievements made during this long association by renovating the field station building and laying a commemorative plaque adjacent to the Nora Creina Road.



Restored field station at the Dawson's family property at Robe

In the early 1950's CSIRO workers Dr Mary Dawbarn, Denise Hine and Patricia Hughes demonstrated that Co deficiency in sheep resulted in a drastic fall in vitamin B₁₂ production by the rumen micro-organisms. Cobalt is a constituent of vitamin B₁₂ that does not occur in plants, but is synthesised by rumen microbes. It is the vitamin animals need, not the cobalt. Considerable progress was made in the 1950s and 1970s by the CSIRO scientists Hedley Marston, Dick Smith, W Osborne-White and Jeff Gawthorne on determining the daily requirements of Co and vitamin B₁₂ and the role of vitamin B₁₂ in intermediary metabolism of the sheep.

In 1953, John Lee and Bob Kuchel (CSIRO) reported that 'phalaris staggers' in sheep (a chronic disorder afflicting weaners grazing young phalaris in early winter) could also be prevented by administering Co. It was shown that the increased concentrations of Co in the rumen protected animals from the neurotoxin in phalaris: vitamin B₁₂ is ineffective in preventing this disorder

In 1958, Doug Dewey, Hedley Marston and John Lee developed the cobalt bullet (or pellet) and grinder technology. The heavy Co oxide-iron oxide pellet (10 g weight) lodged in the rumen metered out a slow supply of Co to stimulate vitamin B₁₂ production within the rumen. The administered grinder reduced deposits building up on the bullet surface. Although sheep were more susceptible to Co deficiency than cattle, Co bullets (20g weight) were also developed for cattle. Later (1969) Bob Kuckel and Reg Buckley developed a bullet for correcting selenium (Se) deficiency in sheep.

The advances described above on Co were all world-first discoveries and innovations.

In 1942, Dr Ian Mc Donald (CSIR) reported another *world-first discovery* on the description and pathology of *enzootic ataxia* (a nervous degeneration of the spinal cord in lambs and symptomatic of acute Cu deficiency). The incidence of ataxia and the widespread occurrence of steely wool, or abnormal wool crimp (another symptom of Cu deficiency) in SA sheep between 1939 and 1946, (recorded by John Lee and colleagues), attested to the widespread incidence of Cu deficiency in SA at that time.

John Lee in 1951 also showed that the incidence and severity of trace element deficiencies in ruminants in SA fluctuated seasonally and between years.

To celebrate their jubilee (1926 – 1976) the renamed CSIRO Division of Human Nutrition held a symposium in Adelaide that acknowledged the internationally important contributions that pioneering research on livestock nutrition in SA had made over many years. These key advances were frequently published in the Journal of the SA Department of Agriculture and distributed widely to SA farmers.

Pasture research:

Cereals, lucerne and other sown legumes and grasses grown on the soil at the CSIR Robe experimental station failed miserably, often dying at the seedling stage. Only cereal rye and two native grasses grew successfully. By 1938, field trials by Dr David Riceman, Colin Donald (later Professor of Agronomy at the Waite Institute) and solution culture experiments by Dr CS Piper confirmed that these failures could be spectacularly reversed by applying Cu enriched superphosphate. Zinc (Zn) was also required for oats and sown pastures.

The development of the infertile, sandy heath lands for agriculture in the Upper South East region (Coonalpyn Downs) after WWII would not have been possible without combined applications of superphosphate, Cu, Zn, molybdenum (Mo), and for some soils, Mn and cobalt. These combinations of nutrients were required for the establishment *and* persistence of productive pasture species. The legume component of pastures was depressed markedly where Cu was not applied, because the deficiency markedly affected sub clover seed yield. Lucerne did not respond to applied Zn.

In 1986, as part of SA's 150 year celebrations, the Governor of SA unveiled a monument 14 km NW of Keith on the Duke's Highway commemorating the '*Desert Conquest*', made possible by a large number of field studies commencing in the early 1940s by scientists in several agencies. A review of this pioneering work was

prepared for the day by Newton Tiver (formerly Departmental Chief Agronomist) and acknowledges particularly the immense contributions that Dr David Riceman (CSIR), Dr Alf Anderson (CSIR stationed at the Waite) and Kelvin Powrie (who transferred from the SA Department of Agriculture to The University of Adelaide at the Waite) and others made to pasture nutrition in this region.

The *Kelvin Powrie reserve* (towards Keith from the monument) was developed by the Keith community to honour his contribution. Kelvin developed the principles of P and S accumulations in these sandy soils, but also demonstrated that Co was required for growth and improved nodulation and N fixation by sub clover and lucerne on the infertile sands of the Bangham scrub. *This was the first world-wide report of field-grown plants requiring Co.*

In 1940, Dr CS Piper confirmed that Mo was an essential plant nutrient for oats grown in purified solution culture. His experiments were conducted in 1939, the year that Professors Arnon and Stout in USA announced their discovery on the essentiality of Mo for tomatoes.

By 1942, Dr Alf Anderson (CSIR) reported the *world's first field response to applications of Mo* in sub clover pastures grown on acidic ironstone soils at Mr Norman Brookman's property near Meadows in the Adelaide Hills. Later experiments were undertaken at Houghton on Mr DV Chapman's farm. The clover responses were spectacular in terms of yield, plant colour and nitrogen fixation capacity, but pasture grasses were not affected. Previously sub clover had failed in this area, except where plants grew on ash accumulations from timber burning and less so where lime had been applied. The ash contained water soluble Mo and lime increased soil pH thereby improving soil Mo availability to plants. In 1946, Anderson reported that a mere ounce/acre of Mo trioxide or equivalent rates of either sodium or ammonium molybdate optimised yield responses and appeared to have a residual effect for at least 2 years.

Responses to Mo have since been recorded elsewhere in SA, (such as on Kangaroo Island by Ted Carter and Phil Wigg and on acidic soils of the SE region). In WA, Mo responses in wheat have since been reported.

In 1946, Anderson also reported that sown pastures grown on the peat soils at Eight Mile Creek and Rendelsham in the lower SE region responded to Cu and Zn, but not to Mo, iron (Fe) or boron (B). Indeed, different pasture species responded differently to either Cu or Zn, producing marked treatment changes in pasture botanical composition.

Newton Tiver was also intimately involved in these investigations. In 1957, he and Glynn Webber reported in the Department's Journal that sub clover pastures grown on virgin soils between Woods Well and Kingston (adjacent to the Coorong) responded markedly to applications of superphosphate enriched with zinc and copper. Lucerne did not respond to Zn, but did to Cu (a finding duplicated at Keith earlier by Dr Riceman and colleagues). In 1955, Tiver published a paper in the SA Department of Agriculture Journal (May issue) entitled '*Deficiencies in South Australian Soil*' that related known mineral deficiencies to regional soil types across SA. The distribution

of trace element disorders in SA regions was revised in 1986 (Departmental Bulletin 139).

Meanwhile soldier settlers were also developing land on Kangaroo Island. Departmental staff defined the nutritional requirement of virgin soils and their residual value for the lateritic (ironstone) soils of the KI peneplain and other soil types. Experiments and observations by Ted Carter, Henry Day, Phil Wigg and AG Tyson again showed pastures needed P, Cu, Zn and sometimes Mn. Coast disease in sheep occurred on coastal calcareous soils of KI.

Two classical long-term fertiliser sheep grazing trials investigating P and Cu requirements for grazed pastures were established at that time on newly developed iron-stone soils at Parndana (see below for the summary of the Cu trial results). They demonstrated the critical requirement for both P and Cu fertilisers for newly established pastures and sheep productivity. The results also demonstrated the strong residual value of applied fertiliser Cu (1951 to 1960).

SSP applied (kg/ha)	Total Cu applied (kg/ha)	Pasture DM (tonnes/ha) 1951 - 59	Pasture Legume Content* (%)	Legume Cu Status * (mg/kg)	Liver Cu* (mg/kg)	Total wool 1955 – 60 (kg/ha)
188	0	24.9	19	1.6	11	22
376	0	29.5	19	2.1	10	27
188	2	48.3	48	7.5	403	58
376	2	56.4	47	6.1	179	67

SSP = single superphosphate applied each year; Copper applied only in 1951 and 1952; * Determined in 1959/1960.

Dr Peter Brownell at the Botany Department of the University of Adelaide showed that trace amounts of sodium were essential for the growth of *Atriplex* - *another world first discovery*.

Crop research:

Over this early period, Cu, Mn and Zn deficiencies (and sometimes Mo) were detected in cereal, pulse and flax crops grown on a range of soil types.

Wheat, barley and oats grown on the highly calcareous soils near Robe responded markedly to Cu, but not cereal rye (see above). Barley trials on highly calcareous soils west of Warooka on Yorke Peninsula (experiments by RC Scott; Ted Higgs and Max Burton; Ted Carter and Terry Heard) progressively showed strong positive responses to applications of superphosphate, enriched with Mn and Cu (and possibly Zn). Coast disease in sheep was also common in this region. Observations of trace element disorders in crops were also recorded by Reg French when mapping Eyre region soils, vegetation and land use. The trace element status of red-brown earths appeared satisfactory, except for Zn.

Horticultural research:

In 1937, Chief Horticulturalist, AG Strickland (later Director of Agriculture) reported in the SA Journal of Agriculture that symptoms of 'mottle leaf' in citrus could be alleviated with Zn foliar sprays. Orange tree health responded positively to foliar applications of Zn at Berri, Waikerie, Mypolonga and Beetaloo Valley.

Widespread and often severe 'little leaf' symptoms in deciduous fruit trees (pome and stone fruit trees) were reported in 1944 by HK (Harry) Kemp and Allan Beare (later Chief Soils Officer) in the Riverland irrigation areas, lower SE, eastern slopes of the Mt Lofty Ranges, McLaren Vale, Barossa Valley, Clare, Bundaleer Springs and Wirrabara. In many areas, grape vines also exhibited severe, but also sub-clinical deficiency symptoms. Corrective measures included the use of foliar sprays of Zn oxide or sulphate (annual applications were necessary to prevent the re-appearance of symptoms) and swabbing vine shoots with Zn during winter pruning (recommended by Kemp in 1946).

By 1957, WJ (Bill) Baskett reported that in SA: Zn, Mn and Cu deficiencies had been detected in citrus; Zn deficiency in grape vines; Zn, Fe and Mn deficiencies in pome fruit trees; and Zn deficiency in stone fruit and almond trees.

Allan Walkley (University of Adelaide) and Harry Kemp showed in pot experiments with a sandy soil from McLaren Flat that indicator species turnip, swede and oats responded to boron (B) application.

In 1954, Cu deficiency in citrus grown at Murray Bridge was diagnosed by Departmental horticulturalists, David Kilpatrick and Viv Lohmeyer. Bordeaux spraying in spring produced a rapid response and a Zn foliar spray was also required.

Mo deficiency was detected in Brussels sprouts grown in the Adelaide Hills by GW (Greg) Botting and was corrected by applying a molybdate solution to seedbeds before transplanting seedlings. A similar measure was used to prevent 'Whiptail' developing in cauliflower.

Contemporary Advances (Post 1960):

Livestock nutrition:

The veterinary diagnostic laboratories of the Institute of Medical and Veterinary Science (IMVS) located off Frome Road had always worked closely with the SA Department of Agriculture. In 1982, this laboratory function transferred to the Department and in 1994/95 the laboratory facilities and staff were relocated to Glenside and renamed Vetlab.

Copper:

The discovery of thio-molybdates in sheep blood by CSIRO researchers Dr A Dick, Doug Dewey and Dr Jeff Gawthorne in 1975 led to an understanding that thio-molybdenates were the active agents in the interaction between Cu, Mo and sulphur

(S). The bioavailability of Cu to ruminants was reduced by high dietary intakes of Mo and/or S.

In 1990, a survey by Jock McFarlane Geoff Judson and John Gouzos reported that large areas in the SE had adequate pasture Cu levels for cattle but high Mo levels suggesting that cattle were at risk from Mo induced Cu deficiency (termed molybdenosis) and not to simple Cu deficiency. This finding was significant - molybdenosis had to be treated by directly administering Cu to cattle rather than applying Cu to pasture, even though relatively high levels of Cu existed in the pasture from previous fertiliser applications of Cu.

A survey conducted by Richard Merry and Kevin Tiller (CSIRO Soils) and Doug Reuter and Gavin Young (SA Department of Agriculture) also implicated various cruciferous weeds (e.g. Ward's weed, Lincoln weed, wild turnip, wild radish, etc) in the continuing detection of Cu deficiency in sheep in SA. These species had lower Cu, higher S but similar Mo concentrations compared to annual medics.

A series of sheep and pasture trials were conducted on lateritic soils on Kangaroo Island and Fleurieu Peninsula (8 sites) from 1972 to 1974 and on sandy soils of the upper SE region (3 sites) from 1974 to 1977 to investigate the residual value of previously applied fertiliser Cu. These various sites had not received Cu for up to 13 years and 23 years respectively. Cu was applied to a fenced off pasture area at each site and Cu glycinate injections were administered to wethers, but neither pastures nor livestock responded. Cu levels in pasture and sheep blood and liver were in the adequate range, attesting to the long residual value of applied fertiliser Cu. These findings have since been confirmed by long-term Cu trials conducted in WA, where recommended Cu rates lasted for up to 28 years. Thus, at some time in the future Cu will need to be re-applied to these SA soils. The SA work was undertaken by Geoff Judson, Doug Reuter, Bob Hannam, Tom Benson, John Riggs, David Kruger, with Locky McLaren and Jock McFarlane also being involved in the SE trials.

Bob Hannam and Doug Reuter found that the occurrence of steely wool in SA (an indicator of Cu deficiency in sheep) between 1972 and 1975 far less extensive than was found between 1939 and 1946 by John Lee. This was attributed to the widespread use of Cu fertiliser by farmers and its long-term residual value.

In 1971, Mr Doug Dewey (CSIRO) developed Cu oxide particles as an effective oral supplement for treating Cu deficient sheep. This innovative discovery was the forerunner to numerous global evaluation studies, including a number by Geoff Judson and colleagues in SA, on this method of supplementation. Now available commercially worldwide, it has proved to be a safe Cu supplement for livestock.

Field work by Geoff Judson and Peter Babidge in 2002 with sheep grazing pasture with high Mo content at Kybybolite showed that an intramuscular injection of copper heptonate was as effective as an oral dose of copper oxide in preventing Cu deficiency.

Cobalt:

At Mt Benson on the property of Mr Charlie Emery, Bob Hannam, Geoff Judson, Doug Reuter, Locky McLaren and Jock McFarlane (1980) demonstrated the effectiveness of vitamin B₁₂ injections in correcting and preventing Co deficiency in young sheep. As a result of this work, vitamin B₁₂ was produced commercially for use by farmers throughout Australia. The single injection of 2 mg of the vitamin prevented cobalt deficiency in sheep for 2-3 months.

Later studies by Geoff Judson, Peter Babidge, M-J Vawser, Z Chen and L Sansom developed a long-acting vitamin B₁₂ pellet suitable for preventing Co deficiency in sheep for up to 8 months. The vitamin was encased in a biodegradable glycolide/lactide copolymer that slowly released the vitamin from the injection site.

In 1981, Geoff Judson, Bob Hannam, Tom Benson and Doug Reuter were the first to show the value of plasma methylmalonate as an indicator of Co deficiency in sheep.

In 1989, on Fleurieu Peninsula Mike Shallow, Simon Ellis and Geoff Judson showed that wether lambs were more susceptible to vitamin B₁₂ deficiency than ewe lambs.

Farmers using Co pellets in sheep assumed that pellets provided Co for at least 4 years and were disappointed with the new pellets (containing 30 % cobaltic oxide by weight). Field work in the SE region by Geoff Judson, Tim Woonton, Jock McFarlane and Athena Mitsioulis (1995) showed that some Co pellets containing 30% instead 60% cobaltic oxide were ineffective in providing Co for > 1 year, because the source of the cobaltic oxide used in the pellet appeared to affect the effective life of the pellet. A reformulated 30 % cobaltic oxide pellet using cobaltic oxide from another source was found to provided cobalt to maintain adequate vitamin B₁₂ for periods up to 3 years. However, local experience in the SE region also suggests that a single 30% Co pellet does not protect sheep from phalaris staggers.

Recent work in the Sustainable Grazing on Saline Lands program has shown that where salinity has developed in the Upper SE region under the influence of alkaline groundwater, vitamin B₁₂ deficiency has become a serious problem in sheep where the deficiency used to be more marginal.

Further work in 1997 with the Co pellet in beef cattle near Lake George in the SE region by Geoff Judson, Jock McFarlane, Athena Mitsioulis and Peter Zviedrans showed that the pellet was effective for one year and that milk vitamin B₁₂ was a good indicator of vitamin B₁₂ status of cattle. There were some indications from this work that Co deficiency lowered fertility in cattle.

Selenium:

In the 1930s, Ian McDonald and Collins (IMVS) described white muscle disease (WMD) in lambs killed for export. It was suspected the lambs came from KI. But it wasn't until 1957 that Se was discovered to be essential for animals. In 1961, WMD was first shown in USA and NZ to be a symptom of Se deficiency.

The first field cases of WMD in SA were observed in the early 1960s and field studies in the mid 1960s by Drs Miles Pulsford, R Rac and Elizabeth Irving on KI, Coonalpyn Downs and southern Mt Lofty Ranges demonstrated bodyweight

responses in young sheep to Se supplementation. Dr Ken Goodwin (CSIRO) also demonstrated a high incidence of electrocardiograph abnormalities, indicative of WMD, in sheep grazing pastures low in Se in the upper SE and on KI.

Ken Godwin, Bob Kuchel and Reg Buckley (CSIRO) also reported that Se administered to sheep grazing improved pastures increased reproductive performance and Simon Walker, G Hall, D Smith, Ral Ponzoni and Geoff Judson (Departmental staff) observed increased bodyweight and fleece weight responses in young sheep on KI given selenium supplementation.

Surveys of the Se status of livestock on KI by Geoff Judson and John Obst (1975), and in the SE region by Jock McFarlane and Geoff Judson in late 1980s indicated that in general livestock were at risk to Se deficiency in areas with acidic soils, with annual rainfall > 500 mm, and particularly in years when clover growth was prolific.

In 1991, Geoff Judson, Simon Ellis, Brian Kempe and Mike Shallow demonstrated on Fleurieu Peninsula that a subcutaneous injection of barium selenate raised and maintained Se status in ewes for at least 4 years.

In the same year, Jock McFarlane and Mike Riley showed that over 2 years at Lucindale a 0.5 kg wool increase to Se therapy with little response in live weight.

A Se survey of residents on KI, a region of low soil selenium, in early 1980s by Geoff Judson, David Thomas and Kevin Mattschoss showed that residents had similar Se status to Adelaide residents. It was suspected that the Se content of imported flour products was a significant source of dietary Se for the KI residents.

Multiple trace element deficiencies:

In 1972, Dr Adrian Egan (University of Adelaide) demonstrated the first and only SA response in reproductive efficiency of ewes to Zn and Mn supplementation at Moorlands.

Extensive field studies by Geoff Judson, Jock McFarlane, Trevor Brown, Colin Trengove, Tee-Siaw Koh, Simon Ellis, Mike Shallow, Brian Kempe and Dick Turnbull were undertaken from 1984-91 to evaluate soluble glass boluses containing Cu, Co and Se as a supplement for sheep and cattle. These large boluses, when administered orally, were retained in the rumen and slowly dissolved to provide trace elements for up to one year.

In 1982, Geoff Judson, Jock McFarlane, Mike Riley, Michael Milne and A Horne reported a dual deficiency of both Co and Cu in beef cattle at Robe. There was no live weight response to Cu until the primary constraint, Co deficiency, was corrected.

Studies by Tee-Siaw Koh and Geoff Judson (1986) with beef cattle in the lower River Murray swamps showed a body weight gain to Se plus Cu. The response only occurred when both nutrients were administered.

Grazier surveys:

Despite 60 years of research and extension, trace element deficiencies continued to limit livestock productive in SA. A survey by Tee- Siaw Koh (Vetlab) of cattle slaughtered in SA during 1989-91 showed that 22% were at risk from Cu deficiency, 18% at risk from Se deficiency and 6% at risk from Co deficiency. In some regions the risk was as high as 43%, and in some hundreds was more than 50%.

Market research arranged by Geoff Judson and G Taylor in early 1992 identified a number of barriers to the adoption of recommended methods for preventing trace element disorders in livestock. These include: scepticism of the financial advantages from correcting trace element deficiencies; the myth that trace elements are a problem of yesteryear, or someone else's problem; confusion surrounding timing and appropriate treatments for correcting trace element deficiencies; expense associated with animal testing; and prejudice towards use of slow release bullets for preventing trace element deficiencies. As a result of the survey findings, the Department undertook a major extension program to increase awareness of trace element deficiencies in cattle.

Trace elements in plant nutrition:

Plant symptoms:

Symptoms of plant nutrient deficiencies in crops and pastures were described by the pioneering researchers. Since then, Professors Alan Robson (University of WA) and Jack Loneragan (Murdoch University WA) have associated where specific nutrient symptoms first appear on plants with the known mobility of nutrients within plants. Thus, for highly mobile nutrients such as nitrogen, phosphorus and potassium, deficiency symptoms are first exhibited on older leaves, whereas trace element symptoms occur on younger foliage because they are immobile within the plant.

Over the past 20 years, several books describing nutrient deficiencies in a wide range of agricultural crop and pasture species have been published. However, less severe deficiencies (known as subclinical deficiencies or 'hidden hunger') do not exhibit obvious symptoms and rely on plant tests for their detection.

Manganese:

In 1962, barley farmers in the Warooka area of southern Yorke Peninsula reported that their crops were failing, despite applying Mn and Cu enriched superphosphate at sowing time to these highly calcareous sands (containing >80 % lime in the surface soil). Doug Reuter (Soils Branch) and Terry Heard (Agronomy Branch) were directed to investigate this problem and conducted experiments from 1963 to 1969 with able assistance from Angus Weir, Cyril Schubert and Bob Puckridge.

In the first year, Mn foliar sprays were applied to barley that had also received Mn enriched superphosphate at sowing and these foliar applications produced marked and positive responses. The unsprayed crop developed severe Mn deficiency symptoms by early stem extension, irrespective of the amount of Mn applied at sowing, because the soil- applied Mn had been rapidly immobilised by chemical reactions. *This was the first time that foliar trace element sprays had been applied to agricultural crops grown in Australia.*

Later trials investigated the rate, number and frequency of Mn foliar sprays to barley. Fertilisers where Mn was homogeneously incorporated within superphosphate granules during manufacture were also compared to where it was physically mixed after granulation. The former fertiliser proved superior and was marketed as the 'Warooka mix'. The incorporation of elemental sulphur into Mn enriched superphosphate to induce acidity within the zone of fertiliser placement produced only minor improvements. Many experimental fertilisers were tested and were specially prepared by fertiliser chemists Mr Karl Walter and Malcolm Tavender of Adelaide and Wallaroo Fertilizer Limited (AWFL). The requirement for other trace elements and superphosphate rates were also examined during these Warooka investigations.

The final recommendations were to apply Mn and Cu homogeneously blended with superphosphate at sowing followed by two or three Mn foliar sprays. In the final year of this program, Clipper barley (which replaced Prior barley in 1968) yielded 3.4 tonnes/ha.

The success of this work was partly due to the splendid cooperation of the local farmers on whose properties the experiments were conducted – Mr PH (Hardy) Hayes, Keith and Neil Murdock and W (Bill) Baker. The work gave confidence to local barley growers, was extended to other calcareous soils in SA, and also laid the foundation for the use of foliar sprays to correct trace element deficiencies in annual field crops in SA. AWFL subsequently developed four foliar products for correcting Mn, Cu, Zn and Fe deficiencies in field and garden plants.

Later (1984 and 1987), John McEvoy, a Marion Bay farmer working with Professor Robin Graham and Dr Nick Marcar showed coating Mn onto barley seed was an efficient means of supplying Mn to barley during early seedling growth. Sowing barley with high Mn content also worked.

The use of trace element foliar sprays was also used as a field research tool for investigating whether trace element deficiencies existed in other field crops. For example, in the mid 1960s Doug Reuter and Jim Grigg examined yield responses to foliar sprays of Mn, Cu, Zn and Fe applied to wheat and barley grown on 20 calcareous and alkaline soils.

From the mid 1970s, sweet narrow-leaved lupins began to be grown in SA as part of new and more intensive crop rotations. Farmers reported low yields and poor seed quality (a disorder called "splitseededness"). Previous WA research indicated the disorder was caused by Mn deficiency. In the early 1980s, six intensively monitored field trials in the upper SE region and on lower Eyre Peninsula, conducted by Bob Hannam, Bill Davies, John Riggs (Department of Agriculture) and Robin Graham (University of Adelaide) demonstrated that a single aerial spray of Mn at mid-flowering on the primary laterals of lupin crops markedly improved seed yield (from zero up to 2.5 tonnes/ha) and corrected the seed disorder. Much of this work formed part of Bob Hannam's PhD thesis and included work on the use of ultra-low volume Mn sprays applied by aircraft. The trials showed that although lupins did not exhibit any vegetative symptoms, there was a critical need for Mn during seed development, since Mn was not redistributed within the plant. There was also a strong relationship

between this disorder and Mn levels in seed used to grow the crop. A plant test for detecting Mn deficiency at mid flowering was also developed. Many of these findings were later adopted in other southern states of Australia.

During 1980 and 1981, Jock McFarlane (Departmental Soils officer based at Struan) showed that seed yields of irrigated lucerne grown on sandy soils at Keith benefited from Mn foliar spray applications. He also developed Mn leaf analysis criteria for diagnosing the deficiency. Jock considered the deficiency was probably caused by highly alkaline irrigation water being applied to lucerne. At the same time there were also yield responses to foliar applied Cu even where Cu had been routinely applied with superphosphate over many years - the irrigated lucerne did not appear to access this soil applied Cu. Subsequently, a copper-manganese spray product was developed to address both deficiencies and reduce the amount of fertiliser Cu applied.

In 1981, Galleon, (a high yielding feed barley with resistance to CCN) was released and was quickly shown to be extremely sensitive to Mn deficiency and a good indicator of Mn deficient soils. The older varieties, Weeah and Dampier, were more tolerant with Clipper having intermediate tolerance. This work was undertaken on calcareous soils at Port Lincoln and Wangary by Bill Davies (Departmental Soils officer) and Robin Graham, David Sparrow and Julie Ascher (University of Adelaide). In 2004, the high yielding, CCN resistant and Mn-efficient feed barley (cv. Maritime) was released by the Waite barley breeders.

Between 1983 and 1987 Ken Wetherby and Departmental colleagues at Cleve also reported positive responses in Galleon barley to Mn applied at sowing and as foliar sprays on neutral pH siliceous sands on eastern Eyre Peninsula. These soils occupied 120,000 hectares in the region.

In 1986, Dale Lewis and Jock McFarlane reported another world first for SA research - the first *evidence of Mn deficiency* occurring in field-grown safflower (grown on black rendzina soil in the SE region). Mn foliar sprays corrected the deficiency and diagnostic plant tests were developed for its detection.

Sensitive plant tests for diagnosing Mn deficiency were also developed over the years in SA for wheat, barley, lupins, lucerne and safflower.

A series of investigations also showed that Mn deficient cereals are more susceptible to debilitating infection of the root diseases Take all and CCN. Mn adequate plants were more tolerant. Some of these insights came from Nigel Wilhelm's Honours and PhD theses, supervised by Robin Graham and others. Nigel has been with SARDI since 1987. Robin Graham was responsible for a large volume of work conducted into the effects of trace element deficiencies in plants on their resistance to diseases. Trace elements included Mn, Zn and Cu and diseases included powdery mildew, Take-all, CCN, Rhizoctonia and crown rot.

There are many other studies conducted in SA by Department researchers showing that trace element disorders were important constraints to sustainable crop production, even though trace elements were not the major focus for the study. For example, in the Adelaide Hills, heavy applications of lime induced Mn deficiency symptoms in pastures, while at the Tarlee long-term rotation trial, soil acidification caused elevated

soil Mn and aluminium levels in surface soil, suggesting lime may be required especially where high nitrogen fertiliser levels and stubble retention were used in some rotations.

Copper:

In the early 1970s, Peter King examined potential trace element deficiencies in cereal crops grown on different land units in the Wharminda and Stokes area of Eyre region. Responses to foliar sprays of Cu, Zn, Mn, Fe, Mo, and boron (B) were tested in wheat. Yield responses varied greatly across different soils, with the largest responses being to Cu, but deficiencies of other trace elements were confirmed at some locations. Three Cu soil tests were calibrated. This work formed Peter's Masters thesis with the University of Adelaide.

In 1975, Professor Robin Graham reported that acute Cu deficiency in wheat was caused by the production of *sterile pollen* as well as *depressed pollen production*.

This was an *important world-first discovery*. For example, soils at Keppoch were considered to be to be excellent cropping land, but in a wheat-lupin rotation wheat yields declined with each subsequent wheat crop. Jock McFarlane, using a new plant test from WA identified Cu as the limiting nutrient and subsequently established field trials with rates of soil applied Cu and Cu foliar sprays. Although no obvious leaf symptoms were exhibited initially, grain yields were increased from 0.5 (without Cu) to 4 tones/ha (with Cu), indicating the pronounced impact of Cu deficiency on grain development and crop returns. Subsequent work on this same soil type showed that Cu deficiency was intensified with increasing rates of nitrogen fertiliser.

Genetically inherited tolerance to Cu deficient soils, (termed Cu efficiency), was demonstrated in South Australian cereal rye, and shown to be controlled by a single dominant gene in a cross with a Cu-sensitive German variety, Winterroggen, by Professor Robin Graham and Julie Ascher. This trait was then transferred to locally adapted wheats on a small segment of rye chromosome 5RL with the assistance of Professor Colin Driscoll and Dr Ken Shepherd at the Waite. In the absence of applied Cu, the inserted gene tripled wheat yield on a Cu deficient soil at Keppoch and increased yield five times where Cu fertiliser was applied to wheat with the inserted Cu-efficient trait.

In 1978, Professor Graham reported triticale commonly expressed the copper efficiency trait derived from its cereal rye parent, and as well, had efficiency traits for Zn and Mn. Indeed, triticale usually performs remarkably well on highly calcareous soils which are often deficient in Mn and Zn and sometimes Cu.

In glasshouse experiments, Doug Reuter developed sensitive Cu and Zn plant tests in sub clover and other pasture legumes during PhD studies in WA. Subsequently, Jock McFarlane tested these criteria in elegant field trials conducted in the SE region using strawberry clover and two sub clovers. These trials also showed the pronounced effect of Cu deficiency on seed production and on subsequent pasture legume regeneration.

Richard Merry (CSIRO Soils) showed that Cu was strongly retained and accumulated to high levels in surface soils of orchards in SA and Tasmania following regular spray applications of the Cu-containing fungicide, Bordeaux.

Zinc:

In 1984, cereal farmers in SA began using high analysis fertilisers, such as DAP and MAP for the first time instead of using single superphosphate based products. Experience in WA indicated that this change in fertiliser practice could induce severe Zn deficiency in crops, because these refined fertilisers contained much lower levels of Zn contamination (~70 mg Zn/kg) than single superphosphate (~ 400 mg Zn/kg).

Drs Bob Hannam and Nigel Wilhelm (recruited to Pt Lincoln) and John Riggs commenced a research program on several soil types in the Eyre and Murray Mallee regions, and discovered severe Zn deficiencies still persisted in cereals, field peas and medic pastures. At Lameroo (Jim Byrne's farm), yields of medic were nearly quadrupled by applying Zn in rotation trials. In following years at this site the farmer applied Zn and over time observed marked improvements in soil structure, water infiltration, sheep carrying capacity and crop and pasture yields.

Diagnostic plant tests were developed and new methods for correcting Zn deficiency were assessed – cultivating soils following a Zn spray before sowing was most efficient. The residual effectiveness of soil applied Zn (2.5 kg Zn/ha) lasted for 3 years (calcareous clays); 5 to 7 years (calcareous red brown earths); and from 3 to 10 years (mallee loams). Following this Zn research program, sales of Zn fertilisers in SA increased four fold and fertiliser companies coated new fertiliser products with Zn.

They also collated results from commercial plant testing services at the time which revealed that Zn deficiency was a widespread problem in cereal crops across the wheat/sheep zone of SA.

Bob Hannam and University of Adelaide colleagues also showed at Lameroo that severe Zn deficiency intensified Rhizoctonia damage in cereals (i.e. undernourished crops were more susceptible to the root disease).

Meanwhile, Professor Graham and colleagues were investigating Zn efficiency in cereals. Tolerance to Zn deficiency was shown to be a polygenic trait that appears to be important for conferring tolerance to many biotic and abiotic stresses common in the SA cropping environment. It is strongly expressed in all popular wheat and barley varieties grown in SA. An important component of Zn efficiency is a capacity to load more Zn into the grain, which in the next generation enhanced seedling vigour, and disease resistance or tolerance. It may also be important to human health.

Dale Lewis showed the importance of Zn in growing faba beans on the groundwater rendzina soils of the SE region, especially where high levels of P were applied.

Sensitive plant tests were developed for diagnosing Zn deficiency in wheat, sub clover and faba beans, barley, medic and field peas.

Residual Herbicides inducing trace element deficiencies:

A new project was commenced by Nigel Wilhelm and Peter O'Keeffe investigated the impact of herbicides on the nutrition of field crops. This work was undertaken following reports from farmers and advisers that some cereal crops treated with sulfonylurea herbicides performed poorly and had symptoms similar to severe trace element deficiencies. They confirmed that various herbicides (from both group A and group B, but especially the sulfonylurea group) could exacerbate trace element deficiencies. Sulfonylurea herbicides applied pre-seeding to cereals had the most detrimental effect on cereal Zn nutrition, but other trace elements were also affected.

Iron:

In 1963, Peter Marrett reported correction of Fe deficiency in pastures and barley crops grown on rendzina soils in the lower SE. Barley yields were increased 7 fold by applying a single foliar Fe sulphate spray. Subsequently (1976), Mark Seeliger and David Moss corrected Fe deficiency in pea crops grown on rendzina lunettes in the SE region by using two foliar Fe sprays, three weeks apart. Symptoms were most severe under waterlogged conditions, were less evident in drier years and partially disappeared as the soil dried out in spring.

Molybdenum:

Jock McFarlane, Trent Potter and Dale Lewis diagnosed and developed corrective measures (foliar sprays or seed soaking) for molybdenum (Mo) deficiency in sunflower crops grown on acidic pasture soils in the SE region. The Mo deficiency symptoms of dwarfed plants with marginal leaf burn were caused by nitrate toxicity - Mo that is an essential part of the enzyme nitrate reductase.

In 2004, Chris Williams, Norbert Maier and L Bartlett of SARDI reported responses in drip irrigated Merlot grapes to Mo foliar sprays applied pre-flowering at Lower Hermitage, Meadows and Kuitpo. Grape bunch yield, berry size, seed formation and nutrient levels in petioles were all improved. A plant test for detecting Mo deficiency was developed by sampling basal petioles.

Sub soil infertility:

Laboratory leaching experiments using radioisotopes (conducted by Dr Gordon Jones and colleagues from CSIRO Division of Nutritional Biochemistry) on several contrasting SA soils showed that minimal Cu, Zn and Co leached on most soils, but applied Mo and Se (both anions) did leach.

In addition, more recent testing of SA soil profiles by the Department's soil survey team (led by David Matschmedt) reported that many SA agricultural soils have accumulated reasonable trace element levels in their surface layers, but have much lower levels in their subsoils.

This prompted Professor Robin Graham to place nutrients (N, P and trace elements) throughout the subsoil on 15 representative SA soil types (called 'grave sites'). Over

the following years as farmers cropped over the sites this treatment (one of the 9 treatments) showed marked improvements in crop yield – up to seven times farmers' yields of biomass and up to three times farmers' grain yields, indicating that impoverished subsoils may be limiting yield potential. These benefits were observed for up to a decade post application. There was no benefit to soil physical disturbance alone.

So how could farmers improve the infertile nature of their subsoils? Enter Dr Bob Holloway and his team at the Minnipa Agricultural Research Centre and colleagues from CSIRO Land & Water. In 2001, they reported that Zn nutrition and uptake in wheat grown on grey calcareous soils on upper EP was improved where Zn, P and N were applied in solution (known as fluid fertilisers) either as a pre-sowing subsoil treatment or banded in surface soil at sowing. The fluid fertiliser was superior to traditional granular fertilisers both for the supply of phosphorus but also for trace elements.

Subsequently, Sam Doudle and her Minnipa team established that a mix of N, P, Zn, Mn and Cu fertilisers could double cereal yields on deep infertile sands on Eyre Peninsula by deep ripping the fertilisers to a depth of 40 cm. Most of the benefit from this technique was due to locating the fertilisers at depth rather than from the deep ripping or the rate of fertilisers used.

These findings are now being extended by Nigel Wilhelm, Sam Doudle and Brendon Growden (SA Dept of Agric, Pt Lincoln) who have demonstrated the benefits from these deep placed fertilisers continued for at least three years and that canola and lupins also benefit from this approach. This work is now focussing on least cost options for commercial operations.

Boron toxicity:

But other subsoil constraints were also shown to exist and these continue to be active areas of research across southern Australia. The first to be identified was subsoil boron (B) toxicity in barley grown on a red brown earth at Gladstone by Dr Brian Cartwright, Bernie Zarcinas (CSIRO Soils) and Alan Mayfield (former Department of Agriculture plant pathologist).

This disorder has since been shown to be widespread in SA and other southern Australian States and affects not only cereals but also medics and break crops. It is thought to be a relic of the inundation of land by the sea eons ago and the laying down of B-rich sediments. The distribution of B toxic soils in SA was mapped using B concentrations in grain. Halberd wheat was shown to have a level of tolerance and this was attributed to why SA farmers were still sowing this wheat 30 years after its release. By contrast, Warigal wheat and Clipper barley were especially sensitive.

Bob Holloway (Minnipa) and Dr Angus Alston (University of Adelaide) in 1992 reported that subsoil B toxicity depressed wheat yield, root length and crop water use efficiency.

Clearly such a problem had to be tackled by breeding crop varieties that exhibited B tolerance – and this became a new plant breeding objective. One of these traits is

attributed to their roots excluding B, which Jeff Paull, Tony Rathjen and Brian Cartwright showed was genetically controlled in wheat. Much research has since occurred to identify B tolerance in wheat lines that eventually led to the release of B tolerant wheat varieties BT Schomburgk, Krichauff, Yitpi and Kalka. B-tolerant barley varieties have now also been released (e.g. Sloop Vic).

During this period, Departmental Fact sheets were prepared on Cu deficiency in cereals (Peter King); Mn deficiency in cereals (Bill Davies, Doug Reuter and Robin Graham) and Zn in crops and pastures (Bob Hannam, Nigel Wilhelm and Dale Lewis).

Prepared by Doug Reuter (July 2007) with valuable contributions from Geoff Judson, Robin Graham, Ben Robinson, Nigel Wilhelm, Bob Hannam and Jock McFarlane.