Plant nutrition in Australia - past, present and future

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I. Introduction

Australia is in general a stable continent formed from ancient rocks which have been subject to a long history of deep intensive chemical weathering and leaching. This has given rise to soils often containing very little of the vital elements essential for the growth of plants and the life of animals and man. Due to the poor yields or failures of their crops our early settlers depended heavily on food brought from Europe. The development of Australia has been largely the story of developing knowledge in plant nutrition.

This review picks up the tale as the situation existed three decades ago, and traces through developments during the last thirty years. It has been an exciting time. As our understanding of plant nutrition has increased old agricultural land has become more productive and former "deserts" have become prosperous farming areas. Over this brief span of our history, the area of land fertilised has doubled, while for example our wheat yields have increased from 4.85 to 13.14 million tonnes (5 year averages from 1946 to 1950 and 1976 to 1980). But with the development have come problems which we have yet to solve if we are to maintain or increase the present productivity of our agricultural lands.

Firstly a brief sketch will be given of the situation in plant nutrition as it existed in 1950. Then more recent research and practice will be described. Finally, leading on from this, future lines of research which should lead to major benefits will be discussed.

II. Plant nutrition in 1950

A. Essential Elements Recognised

It has long been known that there were ten chemical elements universally indispensable for the growth of higher green plants. These were the major nutrients carbon, hydrogen, oxygen, nitrogen, sulphur, potassium, calcium, magnesium, phosphorous and iron. The last seven were considered to be the essential elements provided by the soil. The strange behaviour of legumes in relation to their soil nitrogen requirements was solved when Hellriegel and Wilfarth proved atmospheric N_2 fixation by nodulated legumes in 1887. In the following year Beijerinck isolated the first nodule bacteria. Studies continued until Fred *et al*. (1) in Wisconsin were able to publish a monograph in 1932 on legume symbiosis including a section on other plants fixing nitrogen.

A dramatic change in this list of indispensable elements took place between 1920 and 1940. In 1922 work in Kentucky (2) presented extensive evidence that manganese was an essential element. Soon after, two ladies working at Rothamsted Experimental Station (3) showed boron to be an essential element for broad bean plants. About the same time, in California (4), use of carefully purified salts and redistilled water showed boron to be essential for cereals as well as legumes. The work also showed zinc to be an essential micronutrient for a wide range of plants. Other studies (5,6) showed that copper was also an element that must be added to this rapidly growing list of indispensable micronutrients. One more was soon to be found, again by workers in California. Arnon and Stout in 1939 (7) produced strong evidence that molybdenum was also necessary for the growth of higher plants. So over this period boron, copper, zinc and molybdenum were also shown to be needed by plants, but only in very small amounts.

These experiments were carried out in carefully controlled experiments with elaborate precautions against contamination. The field situation is very different. There it is not a question of absolute deficiency in total quantity of the element present in the soil, but rather a physiological deficiency arising from insufficient availability of the element to the plant for its needs at each successive growth stage.

B. Importance in Australia

1. Superphosphate

By 1950 about 1.5 million tonnes of superphosphate were being applied to 11 mill. ha of fertilised crops and pastures. This was made up from 764,000 tonnes applied to 6 mill. ha. of crops and slightly less at 714,000 tonnes spread over 5 mill. ha. of pasture. Some of the events and research leading up to these statistics follow. Because of the more complex nature of the legume - Rhizobia symbiosis, nutrient deficiencies were often recognised in legume pastures, or the animals that grazed them, before becoming apparent in cereal crops.

A large number of field experiments had been carried out in practically all the agricultural areas of Australia by 1950. Superphosphate rates figured prominently in these and recommended rates of application were usually based on district rainfall and soil type (often characterised by the type of native vegetation it supported). The residual value of superphosphate was also recognised and fertiliser history taken into account

in recommendations. Despite this, however, farmers tended to apply similar rates of superphosphate to crops and pastures over wide areas with little regard to soil type or paddock history.

Pastures

Benefits from using superphosphate on Australian soils have been obtained since around 1900. Then with the commercial development of subterranean clover from about 1920 onwards, the importance of the superphosphate- legume combination became evident. This was particularly so on the large areas of podsolised soils which are extremely low in available phosphorus and nitrogen and which occur in the winter rainfall zones in the southern half of Australia. On calcareous soils and those with a pH above 6.0 annual medics also became important and their development for commercial seed production was described by Trumble in 1939 (8). In South Australia lucerne was also an important legume in some areas.

Rates of superphosphate used in establishing and maintaining subterranean clover pastures ranged from 63 to 188 kg ha^{-1}. By the second or third year after establishment of the pasture, native grasses had frequently virtually disappeared and extreme clover dominance was common. Then, with the build up of soil nitrogen, annual grasses and weeds invaded the pasture. Both production and quality of the grazing then often declined.

One of the important pieces of research showing the value of superphosphate on subterranean clover and nitrogen fixation was that of Trumble and Donald in 1938 (9). Their research was carried out in the Meadows district of South Australia commencing with new land on a podsolised soil previously growing a sclerophyll forest dominated by *Eucalyptus fasciculosa.* They found no other fertiliser than superphosphate to be necessary to grow subterranean clover, and suggested a dressing of at least 250 ka ha^{-1} for the first three years. Recoveries of phosphorus in the herbage were 20-40% in the year of application, rising to an average of 50% or more of the total applied by the end of three years. The percentage of nitrogen in the herbage rose with increasing phosphate application. Total nitrogen accumulation in the herbage of plots receiving 250 kg ha^{-1} of superphosphate annually, averaged 143 kg N ha^{-1}. No measurements were reported of N accumulation in the soil, although estimates were made of the residual effectiveness of phosphate applied in previous years.

Differential responses to phosphate by subterranean clover, phalaris, lucerne, and other herbage plants were shown by Riceman (10,11). In particular lucerne had a high requirement for phosphate.

Influenced by these and many other field trials, the rate of superphosphate applied to pastures in 1950 averaged 135 kg ha^{-1}.

Crops

The progressive elimination of phosphorus as a limiting factor in crop production proceeded from about 1900 onwards (12). As experience was gained in soil types and rainfall patterns, and as new improved varieties were developed, the area of crops receiving superphosphate steadily increased. As with subterranean clover, wheat grown on new land showed a response to higher levels of phosphate than in later years. Initial applications of 210 kg ha^{-1} of superphosphate were not uncommon. However, in a number of experiments on the superphosphate requirements for growing wheat in Western Australia (13), about 126 kg ha^{-1} were needed for medium and heavy soils, with about 146 kg ha^{-1} for light soils and sandplain country. It was found that where land had been fertilised for many years these rates could be reduced.

By 1950 the average use of superphosphate on fertilised crops was about 126 kg ha^{-1}. However, some 3 million hectares of crops were grown without fertiliser largely on the more fertile soils of New South Wales and Queensland.

2. Nitrogen

In 1950 some 40,000 tonnes of nitrogen fertilisers were imported into Australia and this was supplemented with sulphate of ammonia produced as by-products from industry. No other form of nitrogenous fertiliser was produced in Australia, and its use was largely confined to horticultural crops and sugar cane.

The nitrogen requirements of cereal crops were commonly met by using a rotation in which a long period of fallow preceded a wheat crop. During the fallowing period, soil organic matter was decomposed to produce ammonium ions and nitrates. This breakdown of organic matter and loss of soil nitrogen was studied in two experiments on red brown earths (14). After 16 years cultivation, the total nitrogen content of the top 10 cm of soil decreased from 0.158 to 0.094 per cent, and after 20 years cultivation, from 0.222 to 0.135 per cent. In reviewing the major wheat soils of South Australia in 1949, Cornish (12) concluded that the nitrogen required by the crops had been drawn almost entirely from soil reserves under the exploitative systems of cropping generally employed.

By 1950 the use of a period of legume pastures after cereal cropping was becoming more common, but there were few measurements of the actual amounts of nitrogen contributed to the soil by subterranean clover or annual medics.

3. Potassium and Sulphur

Potassium deficiency has been known for many years in situations where exhaustive cropping or especially regular cutting and removal of hay takes place. Response to potash fertilisers were reported by Twentyman in Victoria in 1938 (15), Trumble and Ferres in 1946 in South Australia (16), and Rossiter in 1947 in Western Australia (17). But practical applications of potassium were limited to intensive farming situations by the high cost of the amounts of fertiliser required and the necessity for frequent dressings.

Sulphur deficiency has been largely obscured in Australia by the presence of calcium sulphate in superphosphate; the level of sulphur in the fertiliser often exceeding that of phosphorus. However, response to applied sulphur on the basalts and granites of the southern tablelands of New South Wales were shown in 1950 (18).

4. Trace Elements

a. Early responses

Following the earlier overseas work using purified solution cultures, it was not long before field occurrences of manganese, boron, copper, zinc and molybdenum were identified in Australia. In Victoria Forster and Hore in 1939 (19) found zinc deficiency related to disease in cereals. In the same year Riceman and Donald (20) reported responses to copper on calcareous sands in South Australia. Shortly afterward Anderson (21) described responses to molybdenum in subterranean clover growing on a laterised, podsolised soil in South Australia. Later Riceman (19,22) commenced a series of experiments on the "Ninety Mile Desert" in S.A. and showed responses to both Cu and Zn on Laffer Sand growing subterranean clover and lucerne.

Western Australia was not far behind. Dunne and Throssell in 1948 (23) showed responses on wheat to copper and zinc and responses to copper and zinc on oats (24). The later responses were obtained on newly-cleared land at four sites widely spread through the agricultural areas. Then in 1950 Dunne found applied molybdenum to regenerate an old run-down subterranean clover pasture (25).

b. Copper and zinc

Work in South Australia showed that although both lucerne and subterranean clover responded to copper on deficient soils, seed set in sub-clover was particularly dependent on an adequate copper supply. Striking effects of copper on wool production and animal health also resulted from both direct administration to the animal or application to the pasture (26).

On deep siliceous sands in South Australia, Riceman (27) showed responses to copper and zinc in subterranean clover. However, lucerne did not respond to applied zinc and phalaris responded mainly to the increase in soil nitrogen due to growth of the legumes. Rates of copper and zinc required were about 1.0 kg ha-1 of the element as a soluble salt or oxide.

c. Molybdenum

Anderson and Thomas in 1946 showed that molybdenum, unlike copper and zinc, is primarily concerned in symbiotic nitrogen fixation (28). Direct effects on the host legume were slight by comparison. Adverse effects on grazing animals were found when plants contained in excess of 10 p.p.m. molybdenum and low copper values. Applications of lime stimulated symbiotic nitrogen fixation by increasing the availability of molybdenum to the legume (29).

By 1950, responses to applied molybdenum had been found over a wide range of soils in southern and eastern Australia by Trumble and Ferres (16), Anderson (30), and Rossiter (31). Deficiencies were mainly found on leached soils with a pH less than 7.0. Rates of application required about 60 g ha^{-1} of the element as a soluble salt or oxide.

d. Cobalt

Cobalt deficiency in sheep and cattle grazing pastures in the south coastal areas of Western Australia, was shown by Underwood and Filmer in 1935 (32) and Underwood and Harvey in 1938 (33). At the same time, "coast disease" of sheep grazing on the calcareous sandy dunes of South Australia was shown by Marsten and Lines to be principally due to cobalt deficiency (34,35). Unlike copper deficiency, intravenous injection of the trace element did not cure the disease. The cobalt had to be ingested via the mouth from the pasture or oral injection to be effective. Non-ruminants were not susceptible to the deficiency.

Critical levels of cobalt in the pasture of about 0.07 to 0.08 p.p.m. were found to be needed for healthy animals (36,37). However, by 1950 no pasture response to applied cobalt had been found.

e. Multiple deficiencies

Up to 1950 all nutrient deficiencies found were associated with phosphate deficiency (38), and responses to applied copper, zinc and/or molybdenum were dependent on an adequate application of phosphate.

Nitrogen was almost invariably lacking in the soils which responded to phosphate and trace elements. Hence symbiotic nitrogen fixation through correcting the nutritional deficiencies of legumes was of first importance.

III. Secondary soil salinity

The effects of agricultural development and associated land clearing on the production of secondary soil salinity were well described by Burvill in 1950 (39). Salt lakes of ancient origin have always been a part of the Australian landscape. But by 1950 new saline areas were showing on farms particularly in the wheat belt.

A. Cause and Effect

Many agricultural soils in Australia naturally contain considerable amounts of salt in the profile. This remained fairly stable until the native vegetation was cleared. The crops and pastures replacing this vegetation used less water, and from shallower depths. As a result, new water tables developed after clearing. Springs and seepages formed saline summer moist areas on hillsides, and the rising water tables also brought salt to the surface in previously fertile valley bottoms. These two effects of clearing were most common in the 400-750 mm rainfall zone.

In the 275-375 mm rainfall zone bare salt patches were developing on the heavier soils with little slope. No shallow water table was present.

These soils had always had considerable salt present, distributed down the profile. But after clearing, upward movement of the soil moisture has caused excessive accumulation at the surface.

All these processes had formed areas of saline soil bare of vegetation. Wind and water erosion often followed.

B. Remedies

Remedies recommended in 1950 were as follows. For the low rainfall saline areas without a shallow water table, cultivate, fertilise and sow with a salt tolerant crop such as barley. After harvest the stubble was to be left to stabilise the soil against erosion and minimise surface evaporation.

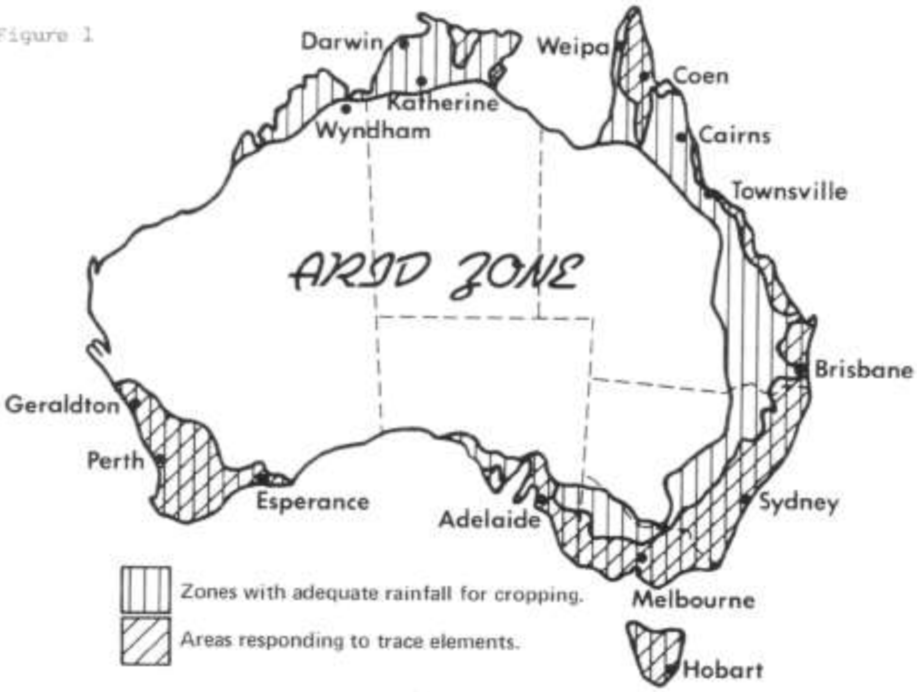
On the saline hillside seeps and valley bottoms with a shallow saline water table, re-establishment of vegetation was recommended using salt.tolerant species such as *PaspaZum vaginatum, Atriplex semibaccata,* or on mild, patchy salt, *Lolium rigidum.* Drainage was thought to be expensive and not very effective due to its localised influence. Tree planting was recommended, but to be effective large areas must be re-established.

IV. Plant nutrition since 1950

A. Nutritional Deserts

The early 1950's saw the development in Australia of the "nutritional deserts". These were large tracts of land close to the coast, receiving good rainfall and bordered by productive agriculture. But their development had not proceeded because on clearing the heath vegetation pastures and crops could not be grown by the use of superphosphate dressings. The key to development lay in the use of fertilisers containing copper and zinc and in some cases molybdenum also. Based on the work of David Riceman and others, the Ninety Mile Desert in south eastern South Australia and the Little Desert in western Victoria, an area of approximately 2.6 mill. ha, have been converted into flourishing farmland.

Figure 1



Commencing about the same time the Esperance Plain, extending from some 100 km east of Esperance to within about 50 km east of Albany on the south coast of Western Australia, has been developed (40,41). The area includes about 1.7 mill. ha.

On the west coast of W.A. the West Midland Plain extending from about 60 km north of Perth to 60 km south of Geraldton and up to 100 km wide is still being developed. The nutritional problems in this class of land were reviewed by Burvill (42).

In Queensland the Wallum heath on the coastal lowlands north and south of Brisbane are under development. The nutritional problems of this area have been outlined by Andrew and Bryan (43). The areas in which plant responses to trace elements have been obtained are shown in Figure 1.

B. Legume Inoculation

Soils of the "Nutritional Deserts" in common with many other areas of new land developed in the last 30 years were acutely deficient in nitrogen. It was uneconomic to supply this deficiency by fertiliser nitrogen. So the symbiotic fixation of atmospheric nitrogen by nodulated legumes was a first requirement. To achieve this end, effective strains of Rhizobia had first to be isolated from plants in the field. Then these strains had to be cultivated in the laboratory and made available to farmers for inoculation of their legume seed prior to sowing. The initial cultures were carried out on agar slopes but on transference to the seed the bacteria quickly died.

It became apparent (44,45) that there was an urgent need for better production methods and adequate supervision and control. Out of this situation there evolved a co-operative advisory and control service, involving the University of Sydney and the New South Wales Department of Agriculture (U-DALS).

In 1954 production of agar cultures changed over to the use of peat. Properly peat-inoculated pelleted seed kept the Rhizobia alive long enough to effectively produce nodules on the developing legume seedling. In acid soils the use of an additional coating of lime was found beneficial. In 1970 U-DALS was replaced by the Australian Inoculants Research and Control Service (A.I.R.C.S.) located at Rydalmere.

This development of high quality strains of Rhizobia for commercially inoculating seed of clover, medic, pea, lupin, and other species is well described by Vincent (46) who played a major role in the work.

C. Symbiotic Nitrogen Fixation

The value of the nodulated legume in building up the soil nitrogen has been measured by a number of workers. In 1954 Donald and Williams (47) found an average of 76 kg of nitrogen to have accumulated in the soil for each 100 kg of superphosphate added. Under a subterranean clover pasture on a light-textured soil Watson in 1963 (48) found soil nitrogen to accumulate at a fairly steady rate of 47 kg ha^{-1} yr^{-1} for five years. In a second experiment (49) the rate of accumulation of soil nitrogen was found to be 81 kg ha^{-1} yr^{-1}, and this rate was not affected by grazing the pasture, mowing and returning the dried plant material, or by mowing and discarding the plant tops.

Inputs of nitrogen from medic pastures have been reported (50). Annual gains ranging from 18 to 93 kg ha^{-1} with occasional inputs of up to 182 kg ha^{-1} of nitrogen over one to two years were found.

Work on lupins (51) carried out by the Western Australian Department of Agriculture at Chapman, Watheroo, and Eneabba, showed an accumulation of 40 to 45 kg ha^{-1} of nitrogen after one year's crop.

D Chlorine and Cobalt

A new essential micronutrient was added to the list of those necessary to the growth of subterranean clover by Ozanne *at al.* (52) in 1957.

They found that a concentration of chlorine in the leaves of about 70 ppm was necessary for healthy growth. The work was carried out in purified inorganic salt solutions.

In similar work using highly purified salt solutions, cobalt was shown to be needed for the growth of subterranean clover in 1960 (53) and lucerne in 1961 (54). This work was followed almost immediately by Powrie in 1960 and Ozanne, Greenwood and Shaw in 1963,who showed field responses by subterranean clover to cobalt fertiliser (55,56). These latter workers found only 140 to 600 g ha^{-1} of cobalt sulphate necessary to give maximum subterranean yield, and that the clover growth was sharply reduced when cobalt contents fell below 0.04 ppm. As cobalt deficiency in animals has often been reported from lush clover pastures, it would be expected that the cobalt requirement of the plants is less than the content of about 0.08 ppm cobalt needed in the fodder for animals (57).

V. Determining fertiliser requirements

A. Development of Models

Since 1950 there has been a great deal of work devoted to studying factors influencing the optimum rate of fertiliser which the farmer should apply. This has led to the development of models of increasing complexity as more factors are taken into account.

In 1963 Colwell (58) put forward a method of calculating the superphosphate requirement, for parts of New South Wales, based on the relationship between yield response and bicarbonate extractable phosphorus in the soil. Later Mullaly *at al.* in 1968 working in Victoria used a method comparing the yield response to superphosphate with several soil extractants (59). About the same time Ozanne and Shaw developed a method in which the phosphate sorbed by the soil in reaching a given equilibrium was used as a measure of the phosphate requirement for clover-based pastures (60). The reason for developing this test was that a soil giving a low value of extractable phosphate has a large or small requirement for applied phosphate depending on whether it has a large or small capacity to sorb and fix applied phosphate. A soil test incorporating both the estimation of bicarbonate extractable phosphate and the phosphate buffering capacity was later published by these authors (61). This method, like the earlier one by these authors, involved equilibrating four or five soil samples to establish a phosphate sorption curve.

Very recently B.S. Dear (private comm. 1982) has developed a technique for determining the phosphate sorption capacity of the soil by equilibrating only two soil samples with phosphate solutions.

Several more elaborate models have been developed more recently, such as the one. put forward by Bennett and Bowden in 1976 (62). This model was later described in more detail (63) and is called "Decide". Among the information used by the model are the maximum yield, present yield, residual value of applied phosphate, soil type, source of phosphate, method and time of application, plant species, management, and economic factors.

B. Factors Needing More Study

No model can hope to encompass all the variables which influence phosphate requirement. For example, we need to know more about the rate at which different soils fix applied phosphate in an unavailable form. Published residual values range from about 20% to 80% effectiveness after one year.

The differences between agricultural plants in response to phosphate may also be large. This was shown when the applied phosphate requirements of four annual pastures and two crops were compared (64).

This and other studies suggest that each crop and pasture species may have a somewhat different yield response curve to applied phosphate.

In addition, work has shown (65) the effects of grazing intensity on the phosphorus requirement of a subterranean-based pasture. The higher the rate of plant removal the higher was the phosphate requirement. Other workers have found a similar relationship.

We also have a lot to learn about the effects of applied phosphorus on pasture quality. For example, a level of phosphorus in the feed higher than that required for maximum pasture production may lead to increased feed intake and body weight gain in sheep (66).

C. Vesicular Arbuscular Mycorrhizas

Most agricultural plants form vesicular arbuscular (VA) mycorrhizas. Potential hosts include the cereals such as maize and wheat, legumes such as the clovers and soyabean, citrus and temperate fruit trees. The main economic significance of these symbiotic associations between fungi and plant roots lies in the ability of the fungal hyphae to proliferate through the soil and greatly extend the effective root mass of the host plant. Nutrients accumulated by the external hyphae are freely transferred to the plant by the fungal strands which permeate the root cortex.

Work on the VA mycorrhizas commenced only recently in Australia. Mosse and Bowen in 1968 examined the distribution of *Endogone* spores in some Australian soils (67). Since that time a number of papers have been published on the role of the VA mycorrhizas in Australian agriculture. This has recently been reviewed by Abbott and Robson (68). The most striking effect of these mycorrhizas is their ability to increase the uptake of phosphate by plants growing under conditions of phosphate deficiency.

The effectiveness of VA mycorrhizas in increasing growth and phosphorus uptake of subterranean clover from slightly soluble sources such as C-grade Christmas Island rock phosphate and calcined Christmas Island rock has been shown (69). In this work the mycorrhizas also increased zinc uptake. It has been shown by a number of workers that the fungal hyphae are not able to absorb phosphate which would be unavailable to the plant root if it was in contact with the phosphate source. However the interconnected network of external hyphae acts as additional catchment and absorbing surface in the soil beyond the depletion zone that would otherwise remain inaccessible to the plant roots. The mycorrhizas may markedly increase the utilization of residual phosphate on fields with a history of phosphate fertilisation.

Our present state of knowledge concerning the VA mycorrhizas has similarities with our understanding of *Rhizobia* in the 1950's. We know of their potential benefits. We also know that they are naturally widespread in our agricultural soils (70). At the present time work is going on to select and culture particularly effective species of the fungi and devise methods of inoculating crops and pastures to establish the desired mycorrhizas. That this is possible has been shown by work on subterranean clover (71).

Although techniques of yield inoculation are now available, the economics cannot be assessed at present. Its value in terms of increased crop production and more economic use of applied fertiliser have to be offset against costs of inoculum production and application.

D. Soil and Plant Analysis

Another relatively recent development over the last 12 to 15 years has been the large increase in the number of soil and plant samples collected in the field and sent into laboratories for analysis. Fertiliser requirements are increasingly being determined by the analytical results.

Recommendations and decisions reflect less and less the average district practice, and more the individual farm and particular paddock requirement.

The analyses are being carried out by state government laboratories, major fertiliser manufacturers, and private agricultural laboratories. Typically soil samples are analysed for extractable phosphate, mineral nitrogen, exchangeable potassium, soil pH, and salinity. Normally the analyses for the trace elements copper, zinc, manganese, and molybdenum are carried out on plant samples. Generally the number of soil samples is much greater than that of plant samples, as with annual crops and pastures the farmer wishes to know his fertiliser needs in advance before sowing.

Following this 30 years work on how to determine the optimum fertiliser application rate, some 3 million tonnes of superphosphate were applied in 1980 in Australia. Average rates used were about 85 kg ha^{-1} on cereal crops and 120 kg ha^{-1} on pastures. However, some 5 mill. ha of crop were sown without superphosphate, and the area of pasture fertilised had decreased about 2.5 mill. ha over the previous 10 years.

E. Sulphur and Potassium Deficiency

a. Sulphur

Twenty years of research into sulphur deficiency in Australia was reviewed by Williams in 1972 (72). Sulphur investigations first commenced in the early 1950's following the discovery of sulphur deficiency on soils in the Canberra region. Since then the deficiency has been found to occur extensively in Eastern Australia, in the Northern Territory, and in Western Australia. On some soils - particularly black earths derived from basalt in the New England and Monaro region of N.S.W., the response to superphosphate was shown to be almost entirely due to the sulphur component. This led to the use of gypsum as a fertiliser.

Studies of sulphur accumulated in soils under subterranean clover pastures in Eastern Australia indicated that sulphur is associated with carbon, nitrogen and phosphorus in soil organic matter. In general the proportion of C:N:S in the organic matter was approximately 140:10:1.3. A study of the sulphur cycle in the soil plant animal system was published in 1971 (73).

The role of sulphur in maintaining lucerne yields in the Lockyer valley was shown in 1974 (74). An application of 125 kg S ha^{-1} maintained a vigorous growth for 5 years. Flowers of sulphur, gypsum, or superphosphate were equally effective as sulphur carriers.

Until 1962 reports of sulphur-deficient pastures in Western Australia were confined to coarse-textured soils receiving more than 500 mm of rainfall. However since that time a number of trials on red brown earths have been carried out (75). Sulphur gave no response unless phosphorus was also applied. Both increased the growth of subterranean clover.

By 1975 interest in sulphur deficiency had reached the point where a comprehensive review "Sulphur in Australasian Agriculture" was published in book form (76).

Work continued and in 1977 the effect of sulphur on the growth, sulphur, and nitrogen concentrations, and critical sulphur concentrations of some tropical and temperate pasture legumes was published (77). Field calibration of a soil sulphate test followed in 1981 (78).

The increasing frequency of occurrence of sulphur deficiency is associated with the increasing substitution of other phosphate fertilisers for superphosphate. Triple superphosphate contains only 1.5% S, ammonium phosphate 1% S, double superphosphate 4.5% S, as compared with the 10.5% S in superphosphate. However, some newer products manufactured by spraying ammonium phosphate solution onto crystalline sulphate of ammonia contain 13-16% S as well as 7-10% P and 12-18% N.

b. Potassium

The importance of potassium as a plant nutrient was well recognised by the mid 1950's. The occurrence and significance of potassium deficiency in Tasmanian pastures was described by Paton (79). Clover and rye grass were severely depressed by potassium deficiency, leading to their replacement in the pasture by inferior grasses. Concurrent work on subterranean clover-based pastures in the higher rainfall (1000 mm) areas of Western Australia showed that the application of 250 kg ha^{-1} of potassium chloride could increase the clover content of pasture from 0.4% to 66% (80). In this work it was shown that a tonne of hay could remove 16-32 kg of potassium. In the medium rainfall areas of W.A. it was later shown that subterranean clover needs about 0.2 milli. equiv. of K 100 g^{-1} of topsoil (81). In the sandplain soils in this study the grasses, capeweed, erodium, serradella, lucerne, lupins and cereal crops were not much affected by potassium deficiency, but subterranean clover containing less than 0.8% K in the leaves showed deficiency symptoms. The application of 60 kg ha^{-1} of KC1 cured the deficiency. Measurements on animals showed that 80% of the potassium removed during grazing was returned in the urine.

In 1962 potassium deficiency in the pastures of the south-east of South Australia was described (82). Better growth of clovers as well as grass on urine patches and dung was a good indicator of potassium deficiency, which was further shown by the replacement of clovers with capeweed and silvergrass.

The relationship between root distribution and the uptake of potassium by 15 annual pasture species was studied by Ozanne *at* al.(83). It was found that all species had a high proportion of their roots in the top 10 cm of soil, and took up most of their potassium from this layer. With increasing depth both the concentration of roots and the amount of potassium absorbed decreased. Subterranean clover had fewer roots at 80 cm depth relative to the other species. These authors also studied the influence of seed potassium on emergence and root development in 12 pasture species. The amount of potassium in the seed in all cases was small in relation to the requirement. Seeds of silvergrass and capeweed contained so little potassium that the roots of these species could only penetrate a highly potassium-deficient sand to a depth of 3-4 cm. By contrast lupin seeds contained enough potassium to allow root development to a depth of at least 90 cm (84).

An assessment of potassium and sulphur fertiliser requirements of wheat in Western Australia was carried out in 1968 and 1969 (85). Of 86 sites examined responses to K and/or S were found on only 20. Yield responses were generally small.

The situation in Australia now is that we have large areas of sandy soils which have a low content of exchangeable potassium and contain few if any primary minerals which are weathering to release fresh supplies of available potassium. The cycle of potassium through the soil, plant, animal system is then a fragile one quickly broken down by the removal of hay or silage. But under grazing the losses are small, mainly due to concentration of the potassium in the feed into small areas where the animals urinate.

Likewise losses under cropping are small as a tonne of wheat grain removes only about 5 kg of K. However we must expect increasing areas to become potassium-deficient, and consequently look forward to increased use of potassium-containing fertilisers.

VI. Source of nitrogen

A. Decline of Pasture Legumes

The loss of sown legumes from old established improved pastures has been increasingly observed widely throughout Australia in recent years. The picture is a complex one but important causes of this decline in the nitrogen fixing component of our pastures are as follows.

It has been commonly observed that freshly sown legume pastures may be almost free from any other component. But as the soil nitrogen level builds up herbs and grasses rapidly invade and replace the legume. In one study (86) a newly-sown pasture contained 80-90% subterranean clover but only 20% 10 years later. The fall in soil pH over this period was only 0.15 units.

In other studies on subterranean clover pastures (87,88) a gradual fall of soil pH of up to 1.0 units has been shown over a period of 30-50 years. The causes of this fall are probably at least twofold. One is the build up of soil organic matter and associated cation exchange capacity. The other is that the symbiotic nitrogen fixing process itself may lead to gradual soil acidification if the fixed nitrogen is ultimately partly leached as nitrate.

Use of nitrogen fertilisers during the cropping phase of a rotation may also decrease the soil pH if the nitrogen is supplied in the ammonium form or as urea. However many soils are naturally acid in reaction although they may have been made more so by the above factors.

Whatever the cause of acidity it is usually associated with three problems in relation to the growth of legumes. One is manganese toxicity (89), another is toxic levels of aluminium (88), and the third is nodulation (90). The use of applied lime to correct excessive acidity is a very old practice which is attracting more attention (91-93). Most aspects of problems related to soil acidity are clearly and simply laid out in a recent review (94).

In the paragraphs above the effects of falling soil pH have been discussed. A number of other factors are associated with the disappearance of legumes from Australian pastures. Among these are the effects of increasing cropping frequency. This, with its associated use of herbicides, has led to reduced hard seed reserves and poorer legume regeneration. This in turn, through low host numbers, has led to low Rhizobial numbers in the soil. Other problems have been the widespread incidence of root rots *Pythium* and *Fusarium* spp. and "clover scorch" caused by *Kabatiella caulivora.* The recent spread across Australia of the blue-green aphid and the spotted aphid have likewise decimated many legume pastures. Potassium deficiency and the reduced application rates of phosphate fertiliser have all played their part.

A combination of the above factors has frequently made re-establishment of legume pastures difficult even where rescouring is practised.

B. Australian Nitrogen Fertiliser Industry

Concurrently with the reduction of legume content in pastures we have seen a marked increase in the use of fertiliser nitrogen which has doubled since 1966. Until 1962 sulphate of ammonia was the only nitrogenous fertiliser produced in Australia and all other supplies were imported. The industry now produces a wide range of manufactured nitrogenous fertilisers. Natural gas is the most common feed stock but by-product gases from oil refineries are also used. The major product is urea but ammonia is manufactured and used as the primary product in making ammonium nitrate, ammonium phosphates and ammonium sulphate. The latter is produced mainly as a by-product in smelting operations (95). The trends in usage of N, P and K in fertilisers are shown in Figures 2a and 2b.

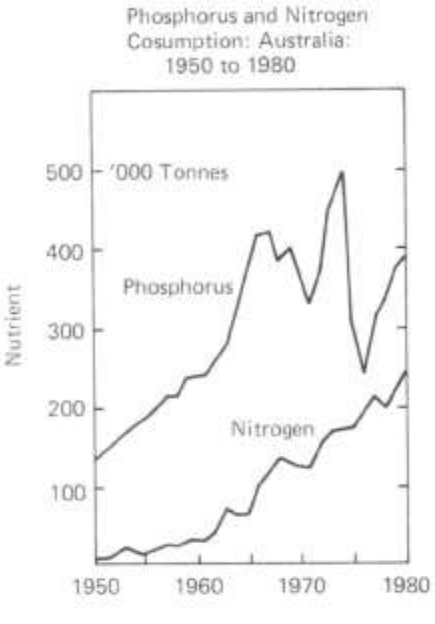


Figure 2a.

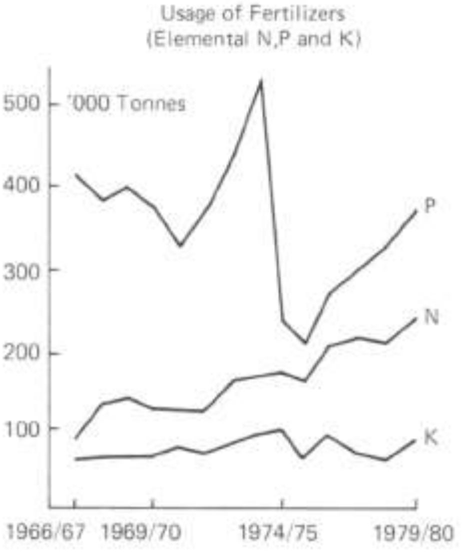


Figure 2b.

Trends in fertiliser usage in Australia (after the Department of Primary Industry (95)).

The increase in use of nitrogen fertilisers has also coincided with the increase in frequency with which the land is cropped. Over the last 30 years cropping has in general been more profitable than the livestock industries. It seems likely that further increases in the area cropped and greater frequency of cropping will continue in the future.

Fertilisers as a percentage of farm costs are one of the largest, if not the largest, single expense the farmer has. A common budget of farm costs is shown in Table 1. It seems unlikely that with the limitations in availability of new land, and the consequent more intensive usage of present farm land that this high fertiliser bill will decrease.

Table 1 farm costs - central wheatbelt - W.A. 1981 - 82

	%
fertiliser	23
seed	7
sprays	5
insurance	1
machinery and labour	45

cartage to siding	3
freight to port	16
	100

VII. Fertilisers and salt amelioration

In Section III of this review secondary salinity following land clearing was discussed in the light of knowledge in 1950. Work since then will now be outlined. The States most widely affected are Western Australia, South Australia, and Victoria.

A comprehensive review of all aspects of salinity following clearing has recently been published in Victoria (96). Wheatbelt salinity in W.A. has also recently been reviewed (97). The increasing use of gypsum on salt affected land is proving effective in some situations under irrigation or high rainfall. The gypsum allows replacement of exchangeable sodium by the less toxic calcium ion provided leaching takes place. Infiltration may also be improved.

Fertiliser is not a cure for salt problems, but growth of cover and consequent water use on salt land can be encouraged by addition of fertiliser. If salting is not too severe nitrogen and phosphorus give responses in some soils. Conventional rates of fertiliser are recommended on mildly salt affected areas. Also nitrogen fertiliser has been found to give profitable returns when applied to the salt-tolerant grass *Puccinellia cilyata* (98).

Other studies have also shown increased yields of grain and greater water use where nitrogen has been applied to crops growing on salt-affected land.

In 1950 Burvill stated that the replanting of large areas of trees was likely to overcome secondary salinity developed after clearing. Calculations of the areas required in catchments in Western Australia indicated that based on native vegetation these areas would have to be about two thirds of the catchments. This would of course be unacceptable on agricultural land unless possibly some form of agroforestry was practised. However, recent work has shown that although the leaf area index (L.A.I.) of native vegetation may be only 2.5, when this land is cleared and replanted with selected fertilised Eucalypts they may develop twice this L.A.I. or even more (99). Such increased L.A.I. is associated with marked increases in water use (100).

Similar increases in the density of foliage of *Pinus* spp. have been obtained by the use of phosphate fertilisers and a ground cover of subterranean clover pasture between the trees (G. Anderson, private comm.). Where fertilisers can increase the water use of tree plantations presumably much smaller areas would be needed than of the native vegetation.

VIII. Trace elements and animals

In the mid 1950's in a comprehensive review on the trace element nutrition of livestock in Australia (101) it was pointed out that fertilizing with molybdenum (Mo), zinc (Zn), boron (B), manganese (Mn), and iron (Fe) may be necessary to overcome deficiencies in plants but not animals. By contrast fertilising with cobalt (Co), iodine (I) and selenium (Se) might be beneficial to the grazing animal. Copper (Cu) requirements for both plants and animals were thought to be approximately equal.

In the same year in a review on the Mo and Cu relationships in animal nutrition (102) it was pointed out that in sheep the low to normal intake of sulphate is less than 0.5 g day^{-1}. However, if the sulphate intake was increased to 2-10 g day^{-1} a fall in blood and tissue Mo concentration and in tissue Cu could result in animals becoming Cu deficient.

Although the toxic effects of Se had been known for many years it was not until 1957 that its essentiality was shown in rats and chicks. Then in 1968 a study on Se in the nutrition of sheep was published in Australia (103). Ryegrass, *Phalaris* and burr medic were found to contain about 0.03 ppm Se while subclover and brome grass contained only 0.015-0.019 ppm. In the following year white muscle disease associated with plant Se levels of less than 0.03-0.05 ppm was reported (104).

In 1969 studies of Zn nutrition in sheep (105,106) showed the requirement of Zn for growth, testicular development and spermatogenesis in young rams. Also the influence of Zn deficiency in ram lambs upon digestibility and utilization of nitrogen and sulphur in the diet. Then in 1972 Zn and Mn deficiency were shown in grazing ewes in South Australia (107).

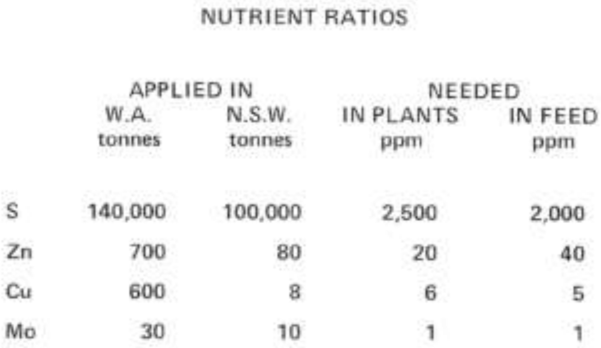
A comprehensive review of Cu deficiency in sheep and cattle in South Australia was published in 1974 (108,109). Methods of preventing the Cu deficiency by the application of Cu sulphate or Cu oxide in superphosphate are discussed.

The interactions between sulphur (S), Cu and other trace elements in the nutrition of sheep was further clarified in 1980 (110). In grazing sheep the concentration of liver Cu was highest in autumn and lowest in late winter. Changes were not related to intake of Cu, but appeared to result mainly from changes in growth rate of the sheep. Pasture S and Mo concentrations were related to Cu storage but they were considered of secondary importance compared with growth rate.

Further work on the Cu status of sheep grazing pastures fertilised with S and Mo was published in 1981 (111). An equation was derived to calculate the quantity of Cu in green forage on offer necessary to maintain hepatic Cu concentration when the forage varied in S and Mo concentration. The results of two experiments suggested that the application of Mo to pasture at commercial rates is unlikely to induce Cu deficiencies in grazing sheep.

The different States of Australia vary widely in the total amounts of trace elements used and in the ratios applied as fertilisers. Western Australia uses the most and New South Wales the least. In Table 2 the ratios of S and of Zn, Cu and Mo containing compounds used in these two states are shown. The apparently anomalous ratio of Cu to Mo used in New South Wales may be worthy of further research into the adequacy of Cu in N.S.W.

Table 2: Ratios of the trace element compounds applied as fertilisers, and the ratios needed in plants and in feed are shown.



NUTRIENT RATIOS

	APPLIED IN W.A. tonnes	APPLIED IN N.S.W. tonnes	NEEDED IN PLANTS ppm	NEEDED IN FEED ppm
S	140,000	100,000	2,500	2,000
Zn	700	80	20	40
Cu	600	8	6	5
Mo	30	10	1	1

IX. Future research in plant nutrition

A. Recognising Nutritional Limitations

Throughout Australia nitrogen supply probably determines crop and pasture yield more than any other element. With the rising costs of nitrogen fertilisers, every effort must be made to maximise symbiotic nitrogen fixation by plants. Subterranean clover is the most widely sown legume, and as discussed in an earlier section it is becoming a minor component of many of our pastures. As such it not only does not make a major contribution to following cereal crops in a rotation, but does not even fix enough nitrogen to give more than about half the potential pasture yield (112).

One area worthy of more study is the limitation of seed set in subterranean clover due to the deficiency of nutrients such as calcium, boron, and manganese which are translocated readily in the transpiration stream, but not in the phloem. Among our pasture species subclover is unique in relying heavily on phloem transport of nutrients to the developing seed. It has been shown that calcium deficiency may markedly reduce seed set while having no visible effect on top yields (113). The insidious nature of this kind of deficiency is that it is only visible in poor reestablishment in the following year when it can easily be attributed to "a poor clover year".

Another aspect of nitrogen fixation by our pasture legumes worthy of examination is the possibility that they may now be commonly infected by ineffective *Rhizobia.* Competition between *Rhizobium* strains for nodulation has recently been shown (114). It is unlikely that the selected effective strains with which the pasture seed was inoculated at sowing are those presently causing nodulation.

New developments in diagnosing nutrient deficiency are also showing promise. In this work the concentration and activity of the metabolic compounds which are dependent on the available nutrient concentration are measured rather than just the total concentration of nutrient present. For example it has been known for many years that the total concentration of iron in leaves bears little relationship to iron deficiency. New techniques in development are the measurement of acid phosphatase (115) to determine the adequacy of phosphate in plant tissues. The use of leaf carbonic anhydrase as an index of active zinc to enable early detection of a deficiency before irreversible biochemical events predispose a large yield reduction is proposed (116). Similarly enzymic diagnosis of copper deficiency through the relationship of ascorbate oxidase activity in leaves to plant copper status has been described (117).

We must also not overlook the possibility of new deficiencies occurring in the field. For example, chlorine deficiency in subterranean clover has been shown in a range of soils in the glasshouse, and possible areas of deficiency in the field in Victoria indicated (118). Also responses to applied vanadium in the field have been reported on pastures in New Zealand.

Interesting new work is also developing in the remote sensing of nutrient deficiencies in crops and pastures through combining aircraft photography and Landsat data (119).

Finally in recognising limitations that should be overcome it is necessary to mention the financial one. Funds for research in plant nutrition in Australia are decreasing in real terms. Also, although fertilisers make up 18% of the cost of agricultural production, only 9% of CSIRO staff working in agricultural research in 1980 were studying soil fertility and plant nutrition.

B. Genetic Engineering

Recent developments in biochemistry have made possible the alteration of the genetic material of living cells so that they produce more, or different, chemicals, or perform completely new functions. The alterations may be made by a variety of techniques including the formation of a hybrid molecule of DNA by joining pieces of DNA from different sources. Work on genetic engineering for nitrogen fixation was sufficiently advanced in 1977 to enable the publication of a book on this subject (120). There is the possibility of transferring nitrogen-fixing ability into non-legume species. At present the prospect of transferring genes for nitrogenase from a bacterium into a plant cell seems quite good (121).

C. Plant Quality

Increasing emphasis in the future will need to be placed on fertilising pasture to meet the nutritional requirements of the grazing animals rather than just providing maximum dry matter or feed on offer. The need to fertilise so that pastures contain the right amounts of phosphorus, zinc, selenium, and other known essential nutrients has been discussed. But we must also find the other elements which are essential for healthy animal growth and the concentrations which are needed. Research may show increased animal production by fertilising with such elements as vanadium, arsenic, and chromium. At present we are preoccupied with supplying the growing pasture plant with its nutrient needs. But throughout most of Australia pastures make only seasonal growth and animals graze for half the year on dry pasture residues. Much more attention must be paid to fertilising the growing pasture so that its dry residues contain adequate amounts of the nutrients needed by the grazing animal, and that the ratios of the nutrients are also within the limits required by the animal.

There is a potentially very large reserve of animal forage produced each year in Australia in the form of cereal stubble - about 22 mill. tonnes in 1981. Research is in progress on the use of alkali treatments to make these crop residues more digestible - e.g. the "Alkalage" process. In these stubble treatments nitrogen, phosphorus, sulphur, and trace elements are usually added as the dry stubble is normally deficient in these. However, it has been shown overseas and in Australia that the application of these elements to the growing crop at the flowering stage by means of a foliar spray usually leads to ready uptake. Increased yields may result. Increased grain and stubble quality almost always are obtained. Research needs carrying out to find to what extent applying these nutrients to the growing crop, when such responses can be obtained, is more profitable than applying them to the dead crop residues.

The quality of plant products for human consumption also warrants more study. Most of our wheat is sold on an increasingly competitive and discriminating overseas market. The bulk of our wheat is low in protein - i.e. Australian Standard White. In some situations it has recently been shown that it may be too low in sulphur, or have too wide an N:S ratio. This leads to poor baking quality. These faults can usually be readily overcome by appropriate fertiliser practice.

The list of essential elements required by humans now includes 15 micronutrients, including of course all those required by animals (122). The list of toxic elements is equally long. So it becomes a problem for the plant nutritionist to not only increase production to feed the world's hungry, but to insure that this increased production contains suitable amounts of the essential nutrients, but does not contain toxic levels of the undesirable elements.

D. Conservation

Our agronomic aims in the past have been heavily orientated to more or less short term production and profitability. The increased frequency of cropping at the expense of pasture has followed from this. However

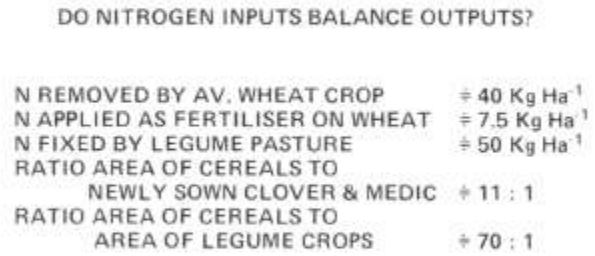
in the future we must look more closely to balancing inputs and outgoings from our agricultural land - particularly those of N, P, K and S. This will need closer monitoring of nutrient cycles, including losses in wind and water erosion, to make sure we are not mining the soil. Table 3 shows our fertiliser practice in relation to plant requirement. Losses of N and P in drainage waters from agricultural lands are receiving increasing attention by environmentalists due to the pollution they are causing in lakes and estuaries. Massive algal growth due to this cause is not un-common. In some instances the concentrations of N and P in drainage water far exceeds that needed in the soil solution for plant growth. So these losses must be viewed as inefficient nutrient usage by the farmer.

	N	:	P	:	K
FERTILISER USAGE					
BEFORE 1973	2	:	6	:	1
NOW	3	:	4	:	1
IN U.K.	7	:	1	:	2
IN PLANTS	10	:	1	:	7–2

Table 3: The relationship between nutrients supplied in fertilisers and plant requirements. The two figures for potassium in plants represent firstly the level in green foliage and the second in cereal grain.

In Table 4 an effort has been made to outline the average balance of nitrogen inputs and outputs in Australia. The figures given are average or common values or the best estimates that can be made from the data periodically given by the Australian Bureau of Statistics. The Table shows that there are eleven hectares of cereals to each hectare of newly sown legume pasture. As has been said earlier the nitrogen contribution of our pasture legumes may be low and certainly needs more study. Legume crops are increasingly being used in cereal rotations, but at the present ratio of seventy hectares of cereals to one of legume crop they cannot contribute much to the soil nitrogen needed.

Table 4:



DO NITROGEN INPUTS BALANCE OUTPUTS?

N REMOVED BY AV. WHEAT CROP	≑ 40 Kg Ha^{-1}
N APPLIED AS FERTILISER ON WHEAT	≑ 7.5 Kg Ha^{-1}
N FIXED BY LEGUME PASTURE	≑ 50 Kg Ha^{-1}
RATIO AREA OF CEREALS TO NEWLY SOWN CLOVER & MEDIC	≑ 11 : 1
RATIO AREA OF CEREALS TO AREA OF LEGUME CROPS	≑ 70 : 1

More accurate figures than those in Table 4 must be obtained and for areas in many cases no greater than the farmer's paddock, if we are to put into the soil as much as we take out or lose from it. Only by so doing can we achieve the objective of long term maintenance of soil fertility in harmony with stable and productive agriculture.

References

1. Fred, E.B., Baldwin, I.L., and McCoy, E.M. 1932. Wisconsin University Studies in Science (5).

2. McHargue, J.S. 1922. J. Amer. Chem. Soc. 44: 1592-1598.

3. Brenchley, Winifred E., and Warington, Katherine. 1927. Annals Botany 41: 167-187.

4. Sommer, A.L., and Lipman, C.B. 1926. Plant Physiol. 1: 231-249.

5. Lipman, C.B., and MacKinney, G. 1931. Plant Physiol. 6: 593-599.

6. Sommer, A.L. 1931. Plant Physiol. 6: 339-345.

7. Arnon, D.I., and Stout, P.R. 1939. Plant Physiol. 14: 599-602.

8. Trumble, H.C. 1939. J. Agric. S.A. 42: 953-958.

9. Trumble, H.C., and Donald, C.M. 1938. Council Sci. Indust. Res. (Aust.) Bull. 116.

10. Riceman, D.S. 1948a. Aust. Coun. Sci. Indust. Res. Bull. 177.

11. Riceman, D.S. 1949. Comm. Sci. Indust. Res. Org. Aust. Bull. 249.

12. Cornish, E.A. 1949. Aust. J. Sci. Res. Series B 2: 83-137.

13. Teakle, L.J.H., and Cariss, H.G. 1943. J. Agric. W.A. 20: 1-28.

14. Clarke, G.B., and Marshall, T.J. 1947. J. Coun. Sci. Indust. Res. Aust. 20: 162-175.

15. Twentyman, R.L. 1938. J. Aust. Inst. Agric. Sci. 4: 210-212.

16. Trumble, H.C., and Ferres, H.M. 1946. J. Aust. Inst. Agric. Sci. 12: 32-43.

17. Rossiter, R.C. 1947. J. Coun. Sci. Indust. Res. Aust. 20: 389-401.

18. Anderson, A.J., and Spencer, D. 1950. Aust. J. Sci. Res. B3: 431-499.

19. Forster, H.C., and Hore, H.L. 1939. Vic. J. Dept. Agric. 37: 157-161.

20. Riceman, D.S., and Donald, C.M. 1938. Coun. Sci. Indust. Res. (Aust.) Pamphlet No. 78.

21. Anderson, A.J. 1942. J. Aust. Inst. Agric. Sci. 8: 73-75.

22. Riceman, D.S. 1945. J. Coun. Sci. Ind. Res. (Aust.) 18: 336-348.

23. Dunne, T.C., and Throssell, G.L. 1948. J. Agric. W.A. 25: 43-46.

24. Dunne, T.C., Smith, S.T., and Cariss, H.G. 1949. J. Agric. W.A. 26: 75-82.

25. Dunne, T.C. 1950. J. Agric. W.A. 27: 118-120.

26. Marston, H.R., Thomas, R.G., Murnae, D., Lines, E.W.L., McDonald, I.W., Moore, H.O., and Bull, L.B. 1938. Aust. Coun. Sci. Indust. Res. Bull. 113.

27. Riceman, D.S. 1948b. Aust. Coun. Sci. Indust. Res. Bull. 234.

28. Anderson, A.J., and Thomas, M.P. 1946. Aust. Coun. Sci. Indust. Res. Bull. 198.

29. Anderson, A.J., and Oertel, A.C. 1946. Aust. Coun. Sci. Indust. Res. Bull. 198.

30. Anderson, A.J. 1948. J. Aust. Inst. Agric. Sci. 14: 28-33.

31. Rossiter, R.C. 1951. Aust. J. Agric. Res. 2: 14-23.

32. Underwood, E.J., and Filmer, J.F. 1935. Aust. Vet. J. 11: 84-92.

33. Underwood, E.J., and Harvey, R.J. 1938. Aust. Vet. J. 14: 183-189.

34. Marston, H.R. 1935. J. Coun. Sci. Indust. Res. Aust. 8: 111-116.

35. Lines, E.W. 1935. J. Coun. Sci. Indust. Res. Aust. 8: 117-119.

36. Filmer, J.F., and Underwood, E.J. 1934. Aust. Vet. J. 10: 83-87.

37. Filmer, J.F., and Underwood, E.J. 1937. Aust. Vet. J. 13: 57-64.

38. Trumble, H.C. 1952. Advances in Agron. 4: 1-65.

39. Burvill, G.H. 1950. J. Agric. W.A. 27: 174-180.

40. Anderson, A.J., and Underwood, E.J. 1959. Scientific American 200: 97-103.

41. Fels, H.E. 1964. Farm Policy 3: 102-105.

42. Burvill, G.H. 1965. J. Agric. W.A. 6: 353-371.

43. Andrew, C.S., and Bryan, W.W. 1955. Aust. J. Agric. Res. 6: 265-290.

44. Brockwell, J.A. 1954. J. Aust. Inst. Agric. Sci. 20: 243-246.

45. Waters, L.M. 1954. J. Aust. Inst. Agric. Sci. 20: 250-251.

46. Vincent, J.M. 1972. J. Aust. Inst. Agric. Sci. 38: 236-249.

47. Donald, C.M., and Williams, C.H. 1954. Aust. J. Agric. Res. 5: 664-687.

48. Watson, E.R. 1963. Aust. J. Agric. Res. 14: 796-807.

49. Watson, E.R., and Lapins, P. 1964. Aust. J. Agric. Res. 15: 885-894.

50. Clarke, A.L., and Russell, J.S. 1977. In "Soil Factors in Crop Production in a Semi-Arid Environment". Ed. J.S. Russell and E.L. Greacen, pp. 279-300. Publ. Univ. of Queensland Press.

51. Anon., 1977. Auuual Report 1976-77 West. Aust. Dept. Agric., p.27.

52. Ozanne, P.G., woolley, J.T., and Broyer, T.C. 1957. Aust. J. Biol. Sci. 10: 66-79.

53. Hallsworth, E.G., Wilson, S.B., and Greenwood, E.A.N. 1960. Nature 187: 79-80.

54. Delwiche, C.C., Johnson, C.M., and Reisenauer, H.M. 1961. Plant Physiol. 36: 73-78.

55. Powrie, J.K. 1960. Aust. J. Sci. 23: 198-199.

56. Ozanne, P.G., Greenwood, E.A.N., and Shaw, T.C. 1963. Aust. J. Agric. Res. 14: 39-50.

57. Marston, H.R. 1952. Physiol. Rev. 32: 66-121.

58. Colwell, J.D. 1963. Aust. J. Exp. Agric. Anim. Husb. 3: 190-197.

59. Mullaly, J.V., Skene, J.K.M., and Jardine, R. 1968. Aust. J. Exp. Agric. Anim. Husb. 8: 52-58.

60. Ozanne, P.G., and Shaw, T.C. 1967. Aust. J. Agric. Res. 18: 601-612.

61. Ozanne, P.G., and Shaw, T.C. 1968. 9th Intl. Congress Soil Sci. Transactions. Vol. 11, pp.273-280.

62. Bennett, D., and Bowden, J.W. 1976. In "Reviews in Rural Science" No. 111, Ed. G.J. Blair, Publ. Univ. of New England, pp.77-82.

63. Anon., 1974. Technotes 1-17, Wagdex 541, West Aust. Dept. Agric.

64. Ozanne, P.G., Howes, K.M.W., and Petch, Ann. 1976. Aust. J. Agric. Res. 27: 479-488.

65. Ozanne, P.G., and Howes, K.M.W. 1971. Aust. J. Agric. Res. 22: 81-92.

66. Ozanne, P.G., Purser, D.B., Howes, K.M.W., and Southey, I. 1976. Aust. J. Exp. Agric. Anim. Husb. 16: 353-560.

67. Mosse, B., and Bowen, G.D. 1968. Trans. Br. Mycol. Soc. 51: 485-492.

68. Abbott, L.K., and Robson, A.D. 1982. Aust. J. Agric. Res. 33: 389-408.

69. Pairunan, A.K., Robson, A.D., and Abbott, L.K. 1980. New Phytol. 84: 327-338.

70. Abbott, L.K., and Robson, A.D. 1977. Aust. J. Bot. 25: 515-522.

71. Abbott, L.K., and Robson, A.D. 1978. New Phytol. 81: 575-585.

72. Williams, C.H. 1972. Sulphur Inst. J.; Summer pp.5-8.

73. Blair, G.J. 1971. J. Aust. Inst. Agric. Sci. 37: 113-121.

74. Dickson, T., and Asher, C.J. 1974. Aust. J. Exp. Agric. Anim. Husb. 14: 515-519.

75. Mason, M.G., Gartrell, J.W., White, L.D., and Stallwood, P. 1975. Dept. Agric. West. Aust. Tech. Bull. No.28.

76. "Sulphur in Australasian Agriculture" 1975. Ed. K.D. McLachlan, Publ. Sydney Univ. Press.

77. Andrew, C.S. 1977. Aust. J. Agric. Res. 28: 807-820.

78. White, P.J., Whitehouse, M.J., Warrell, L.A., and Burrill, P.R. 1981. Aust. J. Exp. Agric. Anim. Husb. 21: 303-310.

79. Paton, D.F. 1956. Tas. J. Agric. 27: 189-204.

80. Fitzpatrick, E.N., and Dunne, T.C. 1956. J. Agric. W.A. 5: 321-326.

81. Toms, W.J., and Fitzpatrick, E.N. 1961. J. Agric. W.A. 2: 763-773.

82. Lines, G.E., and Marrett, P. 1962. J. Agric. S.A. 65: 506-509, 546.

83. Ozanne, P.G., Asher, C.J., and Kirton, D.J. 1965. Aust. J. Agric. Res. 16: 784-800.

84. Ozanne, P.G., and Asher, C.J. 1965. Aust. J. Agric. Res. 16: 773-784.

85. Colwell, J.D., and Grove, T.S. 1976. Aust. J. Exp. Agric. Anim. Husb. 16: 748-754.

86. Watson, E.R. 1969. Aust. J. Agric. Res. 20: 447-456.

87. Williams, C.H., and Donald, C.M. 1957. Aust. J. Agric. Res. 8: 179-189.

88. Williams, C.H. 1980. Aust. J. Exp. Agric. Anim. Husb. 20: 561-567.

89. Flemons, K., and Siman, A. 1970. Agric. Gazette N.S.W. 81: 662-663.

90. DeCarvalho, M.M., Edwards, D.G., Andrew, C.S., and Asher, C.J. 1981. Agron. J. 73: 261-265.

91. Barrow, N.J. 1964. Aust. J. Exp. Agric. Anim. Husb. 4: 30-33.

92. McLachlan, K.D. 1980. Aust. J. Exp. Agric. Anim. Husb. 20: 568-575.

93. Rowe, B.A. 1982. Aust. J. Exp. Agric. Anim. Husb. 22: 100-105.

94. Porter, W.M., Cox, W.J., and Wilson, I. 1980. J. Agric. W.A. 21: 126-133.

95. "Chemical Fertilisers"; 6th Edition 1981. Ed. Dept. Primary Industry. Publ. Aust. Govt. Publ. Service, Canberra.

96. Garland, K., and Duff, J.S. 1981. "Saltland in Victoria". Ed. D. Stone, Publ. Victorian Irrigation Research and Promotion Organization.

97. Malcolm, C.V. 1982. Dept. of Agric., W.A. Tech. Bull. No.52.

98. Clarke, A.J., and Malcolm, C.V. 1976. Dept. of Agric., W.A. Farm Note 29/76.

99. Biddiscombe, E.F., Rogers, A.L., and Greenwood, E.A.N. 1981. Aust. J. Ecol. 6: 383-389.

100. Greenwood, E.A.N., and Beresford, J.D. 1979. J. Hydrology 42: 369-382.

101. Underwood, E.J. 1956. "Trace Elements in Human and Animal Nutrition", Publ. Academic Press Inc., New York.

102. Dick, A.T. 1956. In "A Symposium on Inorganic Nitrogen Metabolism" pp.445-473. Ed. McElroy and Glass, Publ. Johns Hopkins Press.

103. Peirce, A.W., and Jones, G.B. 1968. Aust. J. Exp. Agric. Anim. Husb. 8: 277-287.

104. Gardiner, M.R. 1969. Outlook on Agric. 6: 19-28.

105. Underwood, E.J., and Somers, M. 1969. Aust. J. Agric. Res. 20: 889-897.

106. Somers, M., and Underwood, E.J. 1969. Aust. J. Agric. Res. 20: 899-903.

107. Egan, A.R. 1972. Aust. J. Exp. Agric. Anim. Husb. 12: 131-135.

108. Cunningham, P. 1974. Dept. Agric. S.A. Extension Bull. No. 4.74.

109. Babel, J.D. 1974. Dept. Agric. S.A. Extension Bull. No. 5.74.

110. Purser, D.B., and White, C.L. 1980. CSIRO Symposium on The Importance of Copper in Biology and Medicine, Ed. B.R. McAuslan, Publ. CSIRO, Canberra.

111. Langlands, J.P., Bowles, J.E., Donald, G.E., Smith, A.J., and Paull, D.R. 1981. Aust. J. Agric. Res. 32: 479-486.

112. Cocks, P.S. 1980. Aust. J. Agric. Res. 31: 95-107.

113. Ozanne, P.G., and Howes, K.MPW. 1973. Aust. J. Agric. Res. 24: 839-850.

114. Trinick, M.J. 1982. In "Nitrogen Fixation by Legumes for Tropical Agriculture", Ed. J.M. Vincent, Publ. Academic Press.

115. McLachlan, K.D., and DeMarco, D.G. 1982. Aust. J. Agric. Res. 23: 1-11.

116. Gibson, T.S., and Leece, D.A. 1981. Plant and Soil 63: 395-406.

117. Loneragan, J.F., Delhaize, E., and Webb, J. 1982. Aust. J. Agric. Res. In press.

118. Ozanne, P.G. 1958. Nature 182: 1172-1173.

119. Vickery, P.J., Hedges, D.A., and Duggin, M.J. 1980. Remote Sensing of Environment 9: 131-148.

120. "Genetic Engineering for Nitrogen Fixation" 1977. Ed. A. Hollaender *at ca.,* Publ. Plenum Publ. Corp. New York.

121. "Biotechnology Research and Development" 1981. CSIRO (Aust.)

122. Feinendegen, L.E., and Kasperek, K. 1980. In "Trace Element Analytical Chemistry in Medicine and Biology", Ed. BrAtter and Schramel, Publ. Walter de Gruyter, New York.