Optimization of plant nutrition-improving the efficiency of fertilizer use

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Summary

As a result of the increasing costs of both raw materials and energy there is a need to continue to improve the efficiency of fertilizer utilization in agriculture.

The role of soil and plant analysis, recent advances in fertilizer technology and application techniques, the effects of tillage methods on fertilizer requirement, vesicular-arbuscular mycorrhizas and nutrient efficient species and cultivars have been reviewed in relation to their effects on fertilizer use efficiency.

Short term gains can be expected from increased emphasis on soil and plant analysis to predict fertilizer requirement. In this context there is an urgent need to develop a soil test for nitrogen. An improved understanding of nutrient mobility within plants could also lead to techniques of plant analysis that have more general application.

Manipulation of fertilizer programs to supply nutrients to match plant requirement requires an increased emphasis on application times and methods to reduce leaching losses and conversion to unavailable forms in the soil.

Longer term approaches to increased efficiency of fertilizer use include selection and breeding for nutrient efficient species or cultivars or those adapted to specific problems such as soil acidity or salt. Manipulation of the mycorrhizal symbiosis may also have a role if responsive situations can be identified.

Introduction

Fertilizer use in Australian agriculture represents a major cost to producers and is a substantial energy user. The major fertilizer applied in Australian agriculture is still superphosphate although the application of nitrogenous fertilizers has increased steadily in recent years (Fig. 1). With increasing costs of both raw materials and energy, fertilizer costs are likely to escalate even further. There is therefore a need to continue to improve the efficiency of fertilizer utilization.

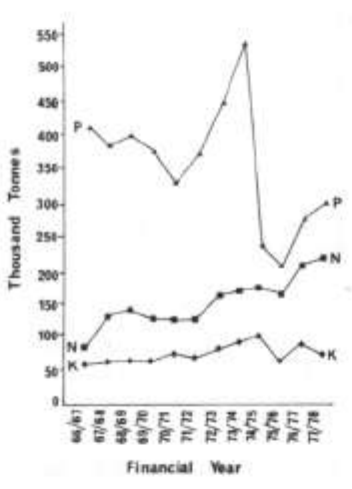

Fig.1: Trends in Australian consumption of fertilizer nitrogen, phosphorus and potassium.

Major pools and processes affecting efficiency of fertilizer usage can be identified by considering the cycling of nutrients within agricultural systems (Fig. 2). We define efficiency here as maximum output of saleable product (or energy) per unit of fertilizer input. This occurs when there are no losses within the system (immobilization in organic matter, reaction with inorganic soil components) or from the system (leaching, erosion or volatilization) other than through product removal (Fig.2). Losses from the system are often proportional to the level of fertilizer application and may represent pollution of surface and/or ground water or the atmosphere.

There are a number of avenues for reducing losses from the system and increasing the efficiency of fertilizer use. Particular approaches which we will consider are:

- Improved precision in decision making on fertilizer use associated with the use of soil testing and plant analysis.
- Development of new fertilizers and application techniques.
- Physical manipulation of nutrients held in unavailable pools.
- Biological manipulation of nutrient pools through the use of vesicular-arbuscular mycorrhizas.
- Selection and breeding of species and cultivars efficient in nutrient use.

Additionally we will also consider some environmental aspects of fertilizer use.

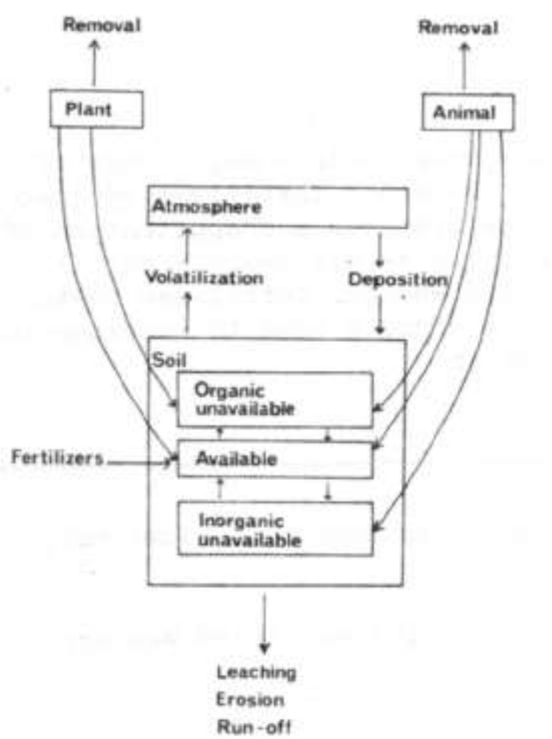

Fig.2: The cycling of nutrients in agricultural systems.

1. Soil testing and plant analysis

Soil Testing

Although soil testing is useful both as a diagnostic tool and for predicting fertilizer rates. there has been a distinct lack of success in developing generally applicable soil tests particularly for nitrogen, phosphorus and potassium. The National Soil Fertility Project (Colwell 1979) emphasized the regional nature of many of the relationships between soil tests and yield responses to fertilizers. Both climate and soil factors contribute to these differences. Extrapolation of calibration data beyond the region in which it was determined would undoubtedly result in false interpretations and misleading fertilizer recommendations.

There are only reliable soil tests available for some nutrients in some regions. For phosphorus a number of regional calibrations are available (Colwell and Esdaile 1968; Palmer et al. 1975; Rayment and Bruce 1979). Many of these are effective for diagnostic use as they discriminate between responsive and non-responsive sites (Rayment and Bruce 1979) but do not have an adequate number of responsive sites to provide a full calibration curve. For sulphur the development of soil tests may be of limited use particularly on leaching soils (see Andrew 1975). Nevertheless responsive sites could be distinguished from non-responsive sites using weighted profile means of 0.5 M $Ca(H2PO4)2$ extractable sulphur (Probert and Jones 1977; Briner et al. 1974). Recent studies have suggested that on leaching sands a measure of sulphate adsorption capacity as well as extractable-sulphate would assist in predicting responsiveness (Yeates unpublished data). A soil test for potassium on pastures is available using a measure of exchangeable potassium alone (Cox 1973) or in conjunction with a measure of non-exchangeable potassium (Vimpany 1967).

There are no generally applicable soil tests for nitrogen. sulphur and potassium for crops or for trace elements for either crops or pastures. Although a number of measures of soil nitrogen correlated well with nitrogen uptake and yield response in glasshouse trials (Storrier et al. 1970) the correlation in field tests was very poor (Storrier et al. 1971). In restricted areas there has been some success in developing soil tests for nitrogen. Total soil nitrogen appeared to be a good predictor of nitrogen status for the growth of wheat on grey and brown clays in the Victorian Wimmera (Tuohey and Robson 1980).

The development of accurate soil tests for nitrogen is a major need in Australian agriculture. Climatic influences on nitrogen mineralization and the lag time between soil collection and planting probably contribute to the poor relationships between measures of soil nitrogen and nitrogen uptake. Additionally responses for both soil nitrogen and nitrogen fertilizer vary markedly between seasons. There is thus a need to move the emphasis in calibration of soil tests from the average season to the "most probable" season. In the absence of suitable soil tests regional recommendations related to soil type and cropping history will need to be improved to increase the efficiency of nitrogen fertilizer use.

Incorporation of soil testing into biological-economic models (Bowden and Bennett 1975; Helyar and Godden 1977) should provide more flexible recommendations that those based on soil testing alone. In such models recommendations can be based on soil tests of individual paddocks, on-farm fertilizer and produce prices, yield estimates and additional economic information relating to financial restraints.

Plant Analysis

Plant analysis is commonly used as a guide to the nutrient status of both agricultural and horticultural crops. The principles and practice of plant analysis have been extensively reviewed (see reviews by Ulrich and Hills 1967; Andrew 1968; Bates 1971; Jones 1972; Leece 1976a). In this review we will only consider two recent developments.

In plant analysis the central relationship is that between nutrient concentrations in the plant and yield. This relationship can be markedly altered firstly by nutrient mobility and secondly by interactions between nutrients within the plant. We will consider each of these factors in turn.

Nutrients differ in the extent of their remobilization from old leaves to new growth. Nutrients such as nitrogen, phosphorus and potassium generally move readily from old leaves to other plant organs in both deficient and adequately supplied plants, although there may be exceptions (Johansen 1979). Other nutrients such as calcium and boron are virtually immobile once deposited in old leaves, irrespective of nutrient status. The mobility of a third group of nutrients which include copper, zinc and sulphur is variable depending on nutrient supply and other environmental conditions (see review by Loneragan et al. 1976). For nutrients which are mobile. analysis of whole tops gives a reasonable indication of the nutrient status of plants. For nutrients which are immobile or variably mobile. concentrations in whole tops will be poor indicators of nutrient status because they reflect the previous supply rather than current status. For these nutrients concentrations in young tissues may give a good indication of nutrient status. Two areas of recent research will now be considered to illustrate these points.

Studies of copper distribution in relation to supply (Loneragan et al. 1976, 1980) suggest that copper concentrations in young leaves will be a good indicator of copper status of plants. The relationship between copper concentrations in the youngest fully emerged leaf and yield was unaffected by nitrogen supply (Hill et al. 1978), moisture stress after flowering (Robson, Loneragan and Snowball unpublished data) or soil type (Brennan, Gartrell and Robson unpublished data). Subsequent samplings from extensive field experiments have confirmed the value of copper concentrations in young leaves for the diagnosis of copper deficiency in wheat crops in the field (Gartrell et al. 1979).

The immobility of sulphur in sulphur deficient plants has led Bouma (1975) to suggest that sulphur concentrations in young leaves should be a better guide to sulphur status than concentrations in whole tops. However, for subterranean clover there was little difference in sulphur concentrations in blades of young leaves (i.e. not at full size) and old leaf blades sampled from plants with either deficient, marginal or adequate sulphur supplies (Spencer et al. 1977). Clearer distinctions may have been obtained if sulphur concentrations in youngest fully emerged leaves were compared with those in whole tops. In subterranean clover and three other species (rape, wheat, oats), the content of sulphate-sulphur expressed as a proportion of the total sulphur content of whole tops was a good index of sulphur status (Spencer et al. 1978; Freney et al. 1978). Unlike either sulphur or sulphate concentrations, critical values of this index did not vary with the age of the plant.

A third nutrient which is variably mobile is zinc. In recent studies zinc-deficient plants maintained higher concentrations of zinc in whole tops than did zinc adequate plants (Leece 1976b; Weir and Milham 1978) producing Piper-Steenbjerg curves and leading to the suggestion that maize plants may contain zinc which is physiologically inactive (Leece 1976b, 1978). An alternative explanation is that the "inactive" zinc is contained in old leaves due to restricted mobility under deficiency.

These studies indicate that an understanding of factors affecting the mobility of a nutrient within plants will enable prediction of the most sensitive plant part to sample for diagnosis of nutrient deficiencies.

Interactions of nutrients within the plant may affect the relationship between nutrient concentrations and plant yield. Examples of such interactions are sodium-potassium (Smith 1974) and iron-phosphorus (Rediske and Biddulph 1953) but not perhaps zinc-phosphorus (Loneragan et al. 1979).

Interactions which occur outside the plant should not affect the relationship between nutrient concentrations in plants and yield, but will affect the relationship between nutrient application and yield. Recently the concept of nutrient balance and nutrient ratios has been re-introduced with the development of Beaufils Diagnostic and Recommendation Integrated System (DRIS)

in a series of papers (Beaufils 1973; Beaufils and Sumner 1976; Sumner 1977a.b,c, 1978). There appears to be little merit in this scheme and some dangers.

There can be a wide range of ratios of concentration of two nutrients without plant growth responding to further addition of the nutrient present in the lower concentration. Moreover. two nutrients may be both deficient for maximum yield but the ratio of their concentrations within the plant may fall within the normal range.

Where multiple nutrient deficiencies occur plant analysis may only indicate the most limiting nutrient. Correction of one nutrient deficiency may induce the deficiency of another nutrient by dilution associated with increased plant growth. However, unless the relationship between nutrient concentrations in plant tops and yield is changed, the deficiencies can be diagnosed successively by considering the concentrations of single nutrients within the plant rather than nutrient ratios.

In conjunction with soil testing and plant analysis opportunities will exist for strategic fertilizer application after seeding. This increased flexibility in terms of post-planting application of fertilizer, either soil application of the mobile nutrients nitrogen, potassium and sulphur or spray application of the immobile nutrients such as copper and zinc, will remove nutrient factors limiting growth. This is particularly important in the use of nitrogen where heavy application at seeding carries the risk of yield reduction through increased moisture stress (Fischer and Kohn 1966) although in a favourable season substantial yield increases could be obtained from a late application.

2. Development of new fertilizers and application techniques

A number of recent advances in fertilizer technology and application techniques including slow release fertilizers and foliar spray application offer increases in fertilizer use efficiency.

Many Australian studies evaluating the agronomic effectiveness of fertilizer sources, methods and times of application and particle size are difficult to interpret because comparisons have been made at constant levels of application rather than at constant output. The advantages and disadvantages of different methods for assessing the effectiveness of phosphorus sources have been discussed by Mattingley (1963); Kwasawneh and Doll (1979); Palmer et al. (1979). Methods and time of application have also been compared along similar lines (Rudd and Barrow 1973).

Leaching losses of the mobile nutrients nitrogen, potassium and sulphur have been recorded particularly on sandy textured soils under high rainfall conditions (Mason et al. 1972; Hingston 1974; Cox 1979 unpublished data). Phosphorus losses have also been recorded from sandy soils (Ozanne et al. 1961). These nutrient leaching losses generally precede the period of maximum nutrient requirements by the plant (Fig. 3) and this suggests that slow release sources and/or time of application can increase the efficiency of utilisation.

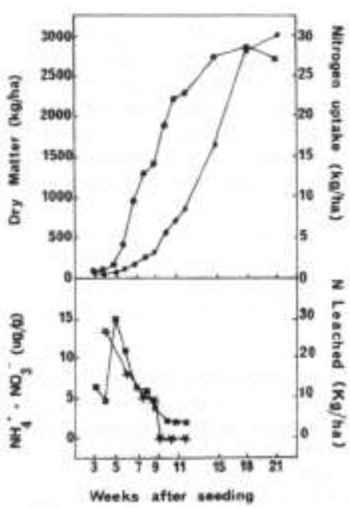

Fig.3: Dry matter production (e) nitrogen uptake (4), leaching losses (*) and soil mineral nitrogen concentrations (0-30cm) for wheat grown with urea applied at 100 kg/ha 4 weeks after seeding. (Mason et al. 1972)

Slow Release Fertilizers

A number of slow release nitrogen fertilizers are marketed commercially including urea-formaldehyde, isobutylidene diurea. resin coated fertilizer and sulphur coated urea.

Field evaluation of urea-formaldehyde on a pangola grass pasture (Digitaria decumbens) indicated high recoveries from a single application of urea-formaldehyde (672 kg Nha-1) than from a single application of urea, ammonium nitrate or sulphate of ammonia (Table 1). Recovery from urea-formaldehyde was equivalent to four dressings of the more common sources (Lowe and Cudmore 1978). These authors also evaluated two experimental products -nitrogen enriched coal (NEC) and Corea (a coal-urea formulation) but these yielded less than conventional fertilizers.

Sulphur coated urea (SCU) has been evaluated in Australia on ryegrass pastures (Maschmedt and Cocks 1976) and on cereals (Mason 1979 unpublished data) with similar results. On pasture SCU gave higher nitrogen recoveries than urea applied as single or split applications although no better than ammonium nitrate (Table 1). The SCU maintained higher levels of mineral nitrogen in the top 10 cm than did the other sources.

TABLE 1: Comparative Nitrogen Recoveries (%) from a Range of Nitrogen Sources.

Nitrogen source	Application	Species		N recovery (%)	Ref.
Urea-formaldehyde	Single	Digitaria decumbens		50	Lowe and
Urea	Single	"	"	29	Cudmore
Urea	2	"	"	38	1978
Urea	4	"	"	44	
Ammonium nitrate	Single	"	"	32	
Ammonium nitrate	2	"	"	64	
Ammonium nitrate	4	"	"	53	
SCU+	Single	Lolium rigidum		65	Maschmedt
SCU++	Single	"	"	78	and Cocks
Urea	Single	"	"	44	1976
Urea	Multiple	"	"	87	
Ammonium nitrate	Single	"	"	88	
Ammonium nitrate	Multiple	"	"	92	

+ Fast release ++ Slow release

The standard potassium fertilizers, potassium chloride and sulphate, are completely water soluble. At present only experimental slow release potassium products are available, the most promising of which are sulphur coated potassium chloride (SCK) and the potassium silicates which have similar patterns of release.

Field evaluations of SCK on mixed subterranean clover-bromegrass pastures (Cox 1979 unpublished data) indicated that SCK was inferior to a single application of KC1 applied at seeding. Furthermore application of SCK at seeding was considerably less efficient as the same quantity of potassium applied as KC1 in four split applications or as a single application four weeks after seeding (Fig. 4). However leaching losses on a sandy soil were considerably less from SCK than commercial KC1 (Fig. 5) suggesting that the rate of release was too slow. These data suggest that the potential use of SCK would be limited to moist sites where it is not physically possible to apply potassium fertilizers after seeding. It may also provide a source of slow release sulphur as SCK contains 20% sulphur as elemental sulphur (Barrow 1971). Mixtures of SC1 with SCK or potassium silicates may provide a pattern of release more compatible with plant requirement.

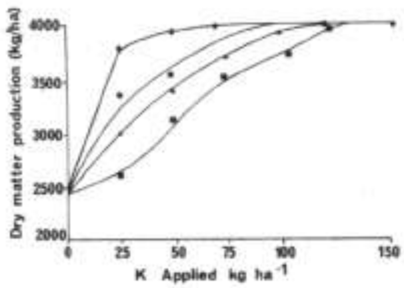

Fig.4: Dry matter production as a function of potassium rate, source (a SCK at seeding) and time of application (A KCI at seeding, • KCZ at 4 weeks, *split applications at 0, 4, 8 and 12 weeks). (Cox unpublished data).

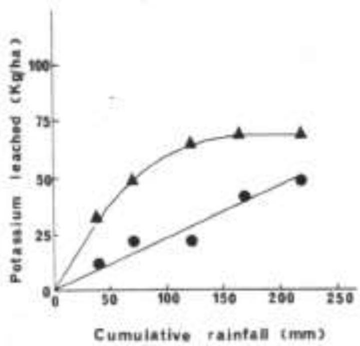

Fig.5: Leaching losses of potassium. from SCK (•) and KCI (A) applied at 150 kg/ha potassium. (Cox unpublished data).

These slow release products are generally much more expensive per unit of nutrient than the more common fertilizers. Because of their lower nutrient content the cost of transport and application costs (energy use) is also greater. Initially these products will only be used for intensive agriculture and recreational activities where labour costs are high e.g. nurseries, bowling greens. At the present time they are too expensive for broadacre use on crops and pastures. In these situations timing of fertilizer application offers much greater scope for increasing fertilizer use efficiencies.

Alternative Phosphorus Sources

Superphosphate is the major phosphatic fertilizer applied in Australian agriculture. With diminishing reserves of high grade rock phosphate, the high energy cost of converting rock phosphate to soluble forms of phosphorus and in some instances an absence of readily-available sulphur, attention has been directed towards other sources of phosphorus. Alternatives which have been examined include calcined C grade rock phosphate (Calciphos), calcined Duchess rock phosphate, direct application of rock phosphate. and the application of rock phosphate with sulphur and sulphur-reducing bacteria (Biosuper).

A recent re-evaluation of published work suggests that the effectiveness of Calciphos relative to superphosphate for the growth of several plant species (wheat, subterranean clover, Guinea grass, Centro) is approximately 0.4 over a wide range of soils and environments (Palmer et al. 1979). However in some situations Calciphos is very ineffective for plant growth (e.g. krasnozem Wright 1975). There may be scope for using Calciphos if these situations can be predicted.

The residual value of Calciphos relative to that of superphosphate has not been satisfactorily examined. There is however reversion of the Calciphos which decreases its availability to plants (Gilkes and Palmer 1979).

Direct application of rock phosphate has been considered also as an alternative phosphorus source to superphosphate. Early Australian studies on the direct application of rock phosphate as fertilizers were reviewed by Jackson (1966). Since that time there have been relatively few studies relating to the use of rock phosphate as a fertilizer in Australia.

In warm wet climates sulphur rock-phosphate mixtures together with a soil inoculum of thiobacilli (Biosuper) have given yield increases comparable to those resulting from superphosphate (Fisher and Norman 1970; Swaby 1975; Jones and Field 1976). In temperate areas with low winter temperatures Biosuper has given poor yield responses (Swaby 1975).

Times and Method of Application

The optimum time and method of fertilizer applications depends on plant requirement and the mobility of the nutrient in the soil. For the mobile nutrients (nitrogen. sulphur and potassium in some soils) delayed application may be most efficient (for example for nitrogen see Mason et al. 1972). Similarly split applications of KC1 are also more effective in increasing growth than either single applications at seeding or at four weeks after seeding (Fig. 4). Relative effectiveness were only 0.08 for application at seeding and 0.42 for application four weeks after seeding relative to that for split dressings. Reduced leaching (Fig. 5) and greater plant absorption explains these differences.

In contrast nutrients which react strongly with soil colloids. for example phosphorus, are best applied at planting or immediately prior to germination. The relative effectiveness of superphosphate broadcast in December or March was only 0.28 compared with 0.48 for super broadcast at seeding where superphosphate drilled at seeding is taken as 1 (Rudd and Barrow 1973). Early application also increases the amount of phosphorus potentially lost through soil erosion and increases the amount entering unavailable pools. It is inefficient fertilizer usage. Despite these results there is a trend towards preplant application of superphosphate to minimise handling of fertilizers at seeding time enabling large areas to be planted an earlier average planting date. Although this reduces the efficiency of phosphorus usage it enhances the efficiency of the whole system. Any large increase in phosphorus fertilizer price relative to the cost of labour and the value of grain may require a re-evaluation of this trend.

Sharp fuel price rises may also reverse this trend because of the double coverage involved.

Foliar Application

Where nutrients are fixed in the soil (phosphorus, iron, manganese) or leached (nitrogen, sulphur, potassium) foliar application can be more efficient than soil application (Wittwer et al. 1963). In the case of the macronutrients (nitrogen, phosphorus. potassium) and nutrients which are immobile in the plant (calcium, boron) frequent applications would be required. This would only be viable for high value crops and is currently practiced in market gardens using overhead sprinkler irrigation systems. For broadacre crops foliar spraying has been limited to the application of corrective sprays such as manganese (Reuter et al. 1973).

An exciting new concept though is the use of post-flowering sprays to increase grain yield (Garcia and Hanway 1976). It has been hypothesised that grain yields can be increased by applying nitrogen, phosphorus, potassium and sulphur to foliage at a time when seed sink demand for these nutrients exceeds the rate of root absorption. These nutrients are then translocated from the older leaves enhancing leaf senescence, reducing photosynthesis - hastening the termination of seed fill and causing the plants to 'self destruct' (Sinclair and de Wit 1976). In legumes the nitrogen fixation process is reduced and may stop altogether. Following the initial substantial yield responses in soybeans (Garcia and Hanway 1976), subsequent work has been inconclusive (Hanway 1977). Photosynthesis was only increased at the final stages of plant growth when seed fill was nearly complete and most leaves had already senesced and dropped (Boote et al. 1978). These workers also found no significant effect on yield.

In Australia, Ozanne and Petch (1978) obtained substantial responses in wheat, lupins and ryegrass seed set although subsequent work was inconclusive (Table 2). The contrasting results for species and sites could be explained on the basis of spray damage to the lupins. The moisture regime after anthesis was better at Badgingarra Research Station. Alston (1979) only found responses to foliar application of nitrogen when moisture stress was low. There are also the conditions under which soil nutrient supply and root absorption would be greatest.

TABLE 2: Effect of Post Flowering Foliar Sprays on Wheat and Lupin Yields at Wongan Hills and Badgingarra Research Stations (Ozanne and Cox unpublished data).

	Yield t/ha			
Species	Wongan Hills		Badgingarra	
	Unsprayed	Sprayed	Unsprayed	Sprayed
Wheat	1.23	1.301†	1.26	1.39*
Lupin	0.61	0.581†	1.06	0.87*

† not significant at P<.05 * significant at P<.05

There is an obvious need for further work to explore the potential yield responses obtainable from foliar fertilization. Spray composition, time of application and the environmental conditions which limit yield need to be defined.

The indirect effects of foliar fertilizer application may also be considerable. Cereal stubbles provide a vast resource of usable energy (Gifford and Millington 1975). Animal utilisation at present is limited by low digestiblity (36 ? 5%) and nutrient content (P 0.08 ? 0.01% and N 0.42 ? 0.14% Pearce et al. 1979). Nutrient spray application by increasing nutrient content (Alston 1979) may improve palatability and digestibility.

Fertilizer Particle Size

The importance of fertilizer particle size has been demonstrated for most fertilizers including superphosphate (Spence and Smith 1978), compound fertilizers (Reuter and Heard 1974) and sulphur (Weir et al. 1963; McLachlan and De Marco 1968).

Although changes in particle size occur during transport and application, control of this parameter is under the direct control of the fertilizer manufacturers. In the production of fertilizers screening and recycling to obtain a product of desirable particle size is relatively simple and low in terms of energy use and cost.

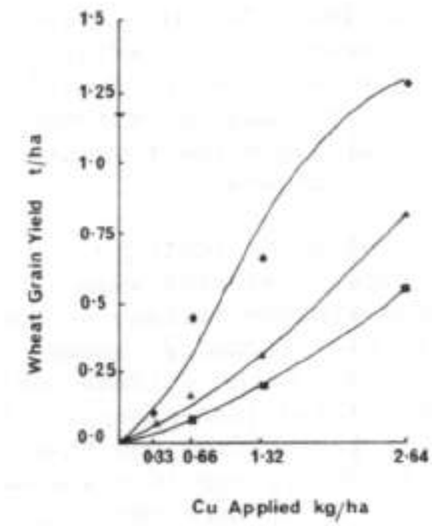

Fig.6: Effect of Cu-Superphosphate granule size on wheat grain yield at Newdegate. (Gartrell, Brennan and Jarvis unpublished data) (41<1.0 mm; A 1.0-3.0 mm; • >3.0 mm).

The effects can be dramatic (Fig. 6). Already minimum nutrient contents have to be specified under Fertilizer Acts and particle size could be an additional requirement.

Concentrated and Compound Fertilizers

In recent years there has been a trend towards high analysis multinutrient fertilizers for cropping. One of the driving factors behind this trend is the emphasis on speed, timeliness in planting and labour saving at seeding time. It is an alternative to applying traditional fertilizers before ploughing and minimises handling at seeding time. Although these products are more expensive per unit of nutrient than traditional products at the fertilizer plant. cost of transport, storage and application is less.

There are some disadvantages of compound fertilizers. Firstly the ratio of nitrogen to phosphorus is fixed. Secondly some compound fertilizers (for example diammonium phosphate) contain little sulphur. Sulphur deficiency in cereals has been reported on a number of light-textured soils (Cox 1968; Colwell and Grove 1976). The incidence of sulphur deficiency in cereals is likely to increase as cropping frequency increases and with declining use of superphosphate.

Along with the trend to concentrated and multinutrient fertilizers is the trend towards bulk fertilizer for savings in bagging charges ($12.10/tonne in Western Australia), and for ease of handling. Advances in bulk fertilizer machinery and handling equipment, largely as a result of farmer innovation, have also been substantial.

With the trend towards larger farms there will be an increased demand for labour saving techniques such as bulk handling and high analysis fertilizers. This saving must be balanced against the need for additional sulphur and trace elements - constituents of the traditional fertilizers such as superphosphate.

3. Cultivation and fertilizer requirements

Most nutrients in soils are retained in organic or inorganic pools that are unavailable to plants (Fig.2). There are few management strategies which can increase the rates of mineralization, dissolution or weathering or reduce the rates of immobilization. precipitation or fixation. In this review we will discuss the effect of cultivation timing and method on the efficiency of nutrient use. This is particularly important since in cereal production rotations are becoming narrower and new cultivation techniques (minimum tillage, stubble mulching) are being introduced. Can we manipulate the release of nutrients from the inorganic and organic pools using these techniques?

Minimum tillage is increasing in use in Australian agriculture. Minimum tillage can influence the mineral nutrition of crops in several ways. Firstly in some situations root growth is restricted under minimum tillage as compared to ploughing (for example, Hamblin and Tennant 1978). Secondly, under cultivation organic carbon and nitrogen concentrations in the surface soil may be considerably lower than under zero or minimum tillage (for example, Fleige and Baumer 1974). The increased organic matter in the surface can have at least two important consequences for crop growth. Soil acidity may increase more in the surface soil under zero or minimum tillage than under more conventional cultivation methods (Shear and Moschler 1969; Triplett and van Doren 1969). Additionally a slower mineralization of organic nitrogen may occur (for example Arnott and Clement 1966) so that nitrate concentrations in the soil solution may be lower under direct drilled crops than under those grown after ploughing (Dowdell and Cannell 1975). The reduced mineralization of organic nitrogen occurring under reduced cultivation was associated with total soil nitrogen being greater by 100 kg/ha in the surface 10 cm after 3 years of direct drilling than after 3 years of normal cultivation on a red brown earth at Rutherglen (Ellington et al. 1979). Apart from nitrogen there may also be greater accumulation in the top 5 cm of soil of other nutrients applied to the surface (for example, phosphorus and potassium. Shear and Moschler 1969; Drew and Saker 1978).

Surface accumulation of nutrients may lead to larger losses associated with erosion (Fig. 2). However wind erosion losses tend to be lower under zero or minimum tillage than under normal cultivation. Delays and a slower rate of mineralization of organic matter may decrease losses of nitrogen, sulphur and perhaps phosphorus by leaching prior to sowing of the crop in some situations.

There have been relatively few comparisons of the effect of cultivation procedure on fertilizer response. In three Australian studies where wheat responded to nitrogen application there was no interaction between cultivation procedure and nitrogen fertilizer requirement for the growth of wheat (Greenwood et al. 1970; Reeves and Ellington 1974; Rowell et al. 1977). In some but not all overseas studies nitrogen fertilizer requirements appeared to be greater in untilled than in tilled soils. (See reviews by Bauemer and Bakermans 1973; Davies and Cannell 1975). There have been very few comparisons of phosphate response after long periods of either minimum tillage or cultivation.

Fallowing, by increasing the mineralization of organic nitrogen, may lead to more rapid declines in soil fertility with cropping. Fallowing almost doubled the net nitrification rate (defined by French 1978, as nitrate nitrogen at seeding {0-60 cm} as a percentage of total soil nitrogen {0-15 cm}). The nitrate released by fallowing may be leached from the root zone on coarse-textured soils. Fallowing may also increase losses of nitrogen from the ecosystem associated with greater wind erosion from a cultivated surface.

There appears to be no conclusive evidence that cultivation technique effects fertilizer use efficiency other than increased short-term nitrogen availability through fallowing.

4. The role of vesicular-arbuscular mycorrhizas

The role of this symbiosis to Australian agriculture and the selection and introduction of desirable inoculant fungi is considered in detail elsewhere (Abbott and Robson in preparation). In this review we will consider only the likely sources of nutrients tapped by the mycorrhizas and the possibilities for manipulating the symbiosis.

Vesicular-arbuscular mycorrhizas (VAM) are symbioses between fungi and plants which can increase nutrient uptake and plant growth primarily by increasing the amount of soil explored.

Several studies indicate that mycorrhizas act largely as an extension of the root system shortening the length of the diffusion path for nutrients which are strongly adsorbed by soil colloids. Firstly the specific activity of phosphorus in plants absorbing from 32P-labelled soil is similar in mycorrhizal and non-mycorrhizal plants (Sanders and Tinker 1971; Hayman and Mosse 1972; Powell 1975). Secondly the effectiveness of mycorrhizas in increasing the uptake of phosphorus from both fixed phosphate (Barrow et al. 1977) and from calcined rock phosphate and C grade rock phosphate (Pairunan et al. 1980) is similar to their effectiveness in increasing the uptake of phosphorus from soluble phosphorus sources.

If mycorrhizal plants are able to lower the phosphorus concentration in the soil solution below that associated with root uptake, greater desorption of phosphorus from soil colloids and greater dissolution from insoluble P would follow. Mosse (1973) considered that there might be a lower threshhold for uptake for the fungal hyphae than for the plant root because on some soils mycorrhizal plants took up phosphorus whereas non-mycorrhizal plants did not. However in solution culture mycorrhizal plants did not show greater phosphorus uptake that non-mycorrhizal plants at a solution phosphorus concentration of 0.1 FM (Howeler et al. 1979). In studies on one infertile Western Australian virgin soil, phosphorus uptake and growth of subterranean clover were similar for mycorrhizal and non-mycorrhizal plants when no phosphorus was applied (Abbott and Robson 1977a, 1978; Pairunan et al. 1980).

Irrespective of the mechanisms involved, to achieve the same yield on at least some soils twice as much phosphorus is required for non-mycorrhizal plants as is required for mycorrhizal plants (Abbott and Robson 1977a; Barrow et al. 1977; Pairunan et al. 1980). From a consideration of the mechanisms involved in increased uptake it is likely that mycorrhizas will increase the uptake of other nutrients which move mainly to plant roots by diffusion (for example. potassium and zinc). Studies elsewhere have demonstrated that zinc deficiency can be corrected by inoculation with mycorrhizal fungi (Gilmore 1971).

What are the possibilities for introducing mycorrhizal fungi into agricultural soils and reducing phosphorus fertilizer use? Almost all agricultural soils contain spores or mycorrhizal roots (Mosse and Bowen 1966; Abbott and Robson 1977b; Hayman and Stovold 1979). Virgin soils commonly contain fewer spores than agricultural soils but roots of native plants growing on these soils are commonly extensively mycorrhizal. However not all soils contain all of the many species of VAM fungi. Moreover the distribution of VAM fungi differs with climatic and edaphic environment as well as with land use (Abbot and Robson 1977b; Hayman and Stovold 1979).

Since species and strains of VAM fungi differ in their ability to stimulate phosphorus uptake (for example, Mosse 1972; Powell 1977; Abbott and Robson 1977a. 1978) it is possible to increase growth at limiting phosphorus supply by inoculating field soils with VAM fungi (for example, Abbott and Robson 1977a, 1978). Responses to inoculation in unsterilized soils do not necessarily represent inherent differences in effectiveness since differences in rate of infection associated with amount and placement of inoculum may have dominated comparisons.

Methods of introducing VAM fungi into the field have been developed (Hall 1979; Powell 1979). The long term persistence of the introduced fungi has however not been examined. Does the absence of a particular species or strain of VAM fungi indicate an inability to persist in that environment? There is a need for considerable research into the effect of soil factors on the colonization and persistence of introduced VAM fungi as well as research directed towards an understanding of the factors controlling the current distribution and abundance of the indigenous VAM fungi. Without this concerted effort it will not be possible to reap the considerable benefits that could accrue from the introduction of more efficient VAM fungi into agricultural soils.

5. Selection of nutrient efficient species and cultivars

Species and cultivars may differ markedly in response to nutrient application (see reviews by Andrew and Johansen 1976; Robson and Loneragan 1976). There have been relatively few studies of variation within our major crops and pastures in response to nutrients.

For wheat, semi-dwarf cultivars responded more to applied nitrogen than did long-strawed Australian cultivars (Syme et al. 1976). However, variation in ability to produce high or near maximal grain yields at low nitrogen supply was small. One difficulty here is that unless cultivars differ in ability to take up nitrogen, variation in yield response will be negatively correlated with grain protein levels. Hence in selecting cereals for ability to grow well at low nitrogen supply most attention should be directed towards efficient absorption and transport. Since in most situations mineral nitrogen levels fall to extremely low levels under cereal crops, rapidity of absorption during early growth and efficient redistribution may increase the recovery of nitrogen in grain and reduces losses from the system, particularly by leaching.

For phosphorus there have been more studies of inter- and intra-specific variation. Differences between species and among cultivars within species appear to be associated more with differences in ability to obtain phosphorus at limiting supply than with differences in internal requirements (see review by Andrew and Jones 1978). Differences among annual pasture species in phosphorus uptake from soil (Keay et al. 1970) in general closely paralleled differences among the same species in phosphorous uptake from well-stirred solutions (Loneragan and Asher1967) . Additionally the specific activity of phosphorus taken up by plants from 32P-labelled soil was similar for all species (Keay et al. 1970) suggesting that plants which differed considerably in phosphorus uptake were obtaining phosphorus from the same labile pool. Nevertheless more rapid or more complete depletion of the soil solution associated with either more rapid or more complete adsorption will increase the amount of phosphate desorbed from the soil colloids and the amount of phosphorus dissolved from insoluble phosphorus sources. Differences between the species (Trifolium subterraneaum, Loliwnrigidum) appear to be related to differences in both root anatomy (root hair density and root diameter) and to differences in ability to lower phosphorus concentrations at the root surface to lower values (Barrow 1975).

As well as interspecific differences. cultivars or varieties within a species may differ in response to phosphorus application (for example, Stylosanthes humilis, Jones 1974; Trifolium repens, Caradus and Dunlop 1978; Trifolium subterraneum, Robson and Collins. unpublished data). For subterranean clover considerable variation occurred within each sub-species. This variation was largely associated with differences in phosphorus absorption rather than differences in phosphorus utilization. Differences in phosphorus uptake were not associated with differences in the extent of mycorrhizal infection. An important finding was that commercial cultivars (for example. Dwalganup, Mt Barker and Yarloop) were amongst the most phosphorus-efficient varieties suggesting that their commercial success may be partly related to an ability to grow well at limiting phosphorus supply.

An interesting approach to the selection and introduction of plants tolerant to nutrient and other edaphic stresses (e.g. acidity) has been described by Burt et al. 1975, 1979 for tropical pasture legumes. Detailed description of the soils at the collection sites has enabled a delineation of likely response of the introduced legumes to soil nutrient supply and to acidity.

Apart from nitrogen and phosphorus, a notable study of genetic variation among plant species is that with copper deficiency in cereals (Graham 1978; Graham and Pearce 1979). Working with rye addition lines, it has been demonstrated that the single gene carrying the copper efficiency of cereal rye can be transmitted to a wheat cultivar. The rye-wheat hybrid Triticale acquired the gene for copper efficiency from its copper efficient rye parent.

The selection of species and cultivars better able to exploit the large reserves of many nutrients in soils does appear to offer a long term solution to increasing the efficiency of fertilizer use.

6. Fertilizers and the environment

Fertilizer usage and farming systems may induce environmental problems which requires action to maintain yields (e.g. acid soil infertility problem) or markets (e.g. heavy metal toxicities).

Development of Soil Acidity

The success of agriculture in southern Australia is largely based on the use of subterranean clover and superphosphate. Although this system improves soil fertility through residual phosphorus, sulphur and nitrogen there is also an associated increase in exchangeable hydrogen and a decrease in pH (Donald and Williams 1954; Williams and Donald 1957). The area which may in time have a pH of 5.0 or less has been estimated at 1.0 x 106 ha in N.S.W., 0.5 x 106 ha in Victoria, 0.1 x 106 ha in S.A. and 4.5 x 106 ha in W.A. (Bromfield 1978).

The use of nitrogen fertilizers can increase soil acidity. Fertilizers containing ammonium or forming ammonium ions as a breakdown product acidify soil. The component reactions of the nitrogen cycle and their effects on soil acidity have recently been reviewed by Helyar (1976) and will not be covered here. The rate of acidification depends on a number of factors including soil type and the rate and source of nitogen applied. In a continuous cropping trial the rate of acidification was greatest with sulphate of ammonia (Fig. 7). Smaller reductions in pH could be expected at lower rates of nitrogen usage and where cropping is less frequent. Sulphate of ammonia will continue to be an important source of nitrogen as it is a by-product in the refining of nickel. Although nitrogen increases production, the addition of lime may have to be considered as a cost of using ammonium forms of nitrogen fertilizers.

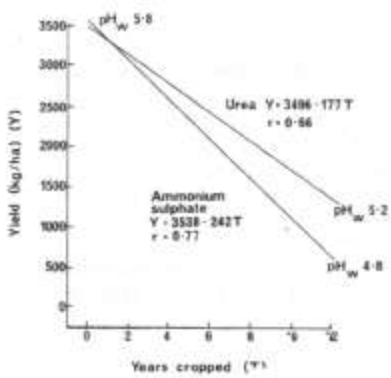

Fig.7: Reduction in yield as a result of continuous cropping using ammonium sulphate or urea applied at 76 kg N/ha/yr. (After Mason and Toms 1975). (pH_W = pH in 1:5 soil water suspension).

Research will be needed to define the problem soils, develop techniques for predicting lime requirement and to screen species and cultivars for tolerance to soil acidity.

A separate problem that will increase in importance in the future is heavy metal toxicities in vegetables. The heavy use of soil applied trace elements (Jones 1964) in association with frequent application of Manozeb and Zineb fungicides has resulted in levels up to 1200 ppm zinc and 1700 ppm manganese (Cox 1979 unpublished data). Apart from specific toxicity effects on plant growth these levels may be a problem for human consumption particularly for crops in which the vegetative component is consumed e.g. lettuce. Most crops limit translocation of heavy metals to the reproductive parts (Cox and Rains 1972). Consistent high dietary levels may result in human health problems (Bloom and Lewis 1973).

Removal of the oldest (wrapper) leaves of lettuce removes a large proportion of the contaminant, however the levels are still high (Table 3).

TABLE 3: Manganese and Zinc Concentrations (ppm) in Lettuce Leaves (Cox 1979 unpublished data).

Plant part		Mn	Zn
		ppm	
(wrapper) -	1	1040	320
leaf	2	273	163
"	3	225	147
"	4	197	131
"	5	224	126

Agronomic research is needed to define the trace element requirements of vegetable crops. Continued usage at current high rates may not only provide risks to public health but could reduce future export markets. Correct usage will also increase the efficiency of utilization.

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