Soil and plant testing in Australia

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The discussion in this paper is confined to broad acre agriculture.

The cost of fertilisers and the price of cereal grain have both risen markedly since the mid 1970's. However since 1982 grain prices have fallen to an extent that fertiliser cost/grain price ratios have trebled in the past 5 years. In some areas of the Australian cereal zone fertiliser costs now represent 30 to 45% of the total variable costs associated with cereal husbandry. As a result, farmers and graziers now need better ways to estimate the fertiliser requirements of their crops and pastures.

Soil and plant analysis are useful tools to help improve fertiliser advice given to farmers. The development and regional calibration of these tests in Australia began in earnest during the early 1960's. This review briefly traces the evolution of this research. It also examines the principles and exposes the potential strengths and weaknesses involved in both forms of testing. We also advance the views that soil and plant testing is being under–utilised by Australian farmers, and that nationally there is room for greater standardisation in testing procedures.

A. Testing in Australia

In 1965, 25000 soil and 6000 plant samples were analysed across Australia by 7 government laboratories and 8 commercial firms for advisory purposes (1). Little testing occurred in WA, SA and Tasmania. Nationally the intensity of testing was extremely low, and largely restricted to sugar cane, citrus, tobacco, fruit tree crops and pastures. Soil tests most commonly reported were pH, salinity, K and lime requirements, and the testing for Colwell P (2) especially in NSW. Plant tests usually included N,P, K and Cl.

During the next two decades many agricultural laboratories were equipped with modern analytical instrumentation, and extensive research was initiated to develop and calibrate additional soil and plant tests.

In 1986, fifteen major Australian testing services processed 87000 soil and 16000 plant samples (excluding tree crop samples) on behalf of farmers for a variety of tests (1 or more tests) on a fee–for–service basis. An additional 13000 soils and 6100 plant samples were analysed at no charge for advisory purposes by 5 government laboratories.

Table 1: Survey results of the approximate number of soil and plant samples processed by 15 major Australian laboratories in 1986

	WA	NT	SA	VIC	TAS	NSW	QLD	TOTAL
	Number of samples analysed							
Soils (x1000)	43+	1.6	6.3	10.1	5.8	19.6	13.8	100.2
Plants (x100)	90.8	28.5	13.8	19.6	0.4	35	33.8	222.2

Clearly the use of soil and plant testing by Australian farmers has increased markedly since 1965, and especially so in WA. Even so, the national intensity of usage is still low (1 soil sample per 470 hectares of arable and improved pasture land) and in some states the usage is well below the national average. Plant analysis is acutely under utilised, but this may now improve with the recent consolidation of plant test criteria published in (3).

Most laboratories offer one or more standard soil test 'package'. Testing methods vary between laboratories: eg the Colwell P test is used in WA, SA, Tasmania, Queensland, Olsen P is used in Victoria and Brays 1 P is used in NSW. Most laboratories now offer a multi-element plant analysis service to their clients.

The four basic testing steps

There are four essential steps in using soil and plant tests effectively: (i) collecting representative samples, (ii) using the most suitable tests, (iii) interpreting the test results, and (iv) providing fertiliser advice (which includes time and rate of application and fertiliser type).

Sampling protocols

The greatest source of error in both soil and plant testing arises during sampling. Errors introduced during sample preparation and chemical analysis are minor by comparison. The adoption of proper sampling protocols must be emphasised.

Soil tests: The chemical composition of soils is known to vary both laterally and vertically (eg 4,5,6). Significant spatial gradients can occur over relatively short distances, but it is expected that the variance will increase with distance (4). The surface soil is usually more enriched than the underlying subsoil.

Erratic temporal variations (both within and between years) in soil test values have also been reported for the mobile anions (nitrate and sulphate), and for the relatively immobile soil nutrients such as P and K (7,8,9). These fluctuations are possibly associated with environmental factors affecting nutrient leaching (10), the dynamics of biomass activity (11) and the mineralisation of soil organic matter. Complex changes in nutrient availability also occur when soils are saturated or submerged (12), however apparent seasonal fluctuations have also be attributed to sampling errors (6).

In southern Australia most tests have been calibrated by sampling in the summer-autumn period to allow farmers to plan their fertiliser needs for the coming season. The time of sampling should conform to that used by the researchers who calibrated the soil tests.

Statistically sound, but efficient patterns and intensities of sampling should be used to cope with the spatial and temporal variations in soil test values. A composite sample of soil cores is required which adequately represents the area being sampled, but avoids sites with unusual features (eg obviously different soil types, drainage lines, stock camps, etc.). The required intensity of sampling varies with the soil test and the variability and fertility status of paddocks (Table 2). Most services recommend a minimum of 20 to 40 cores which appears to be satisfactory.

Suggested sampling patterns include grid, zig-zag and cluster (intensive sampling of small homogeneous areas). Cluster sampling is preferred (4,6) for monitoring the fertility status of pasture soils. Permanently posted sampling paths are a practical means of monitoring fertility changes of cereal soils in successive years.

Table 2: Estimated sampling intensities for various soil tests collected from 25 hectare pasture paddocks of low and high P status (6).

Soil test	Low P site		High P site	
	$*N_{10}$	$*N_{20}$	N_{10}	N_{20}
Colwell P	25	6	36	9
Bray-1 P	71	18	98	25
Colwell K	78	20	29	8
Soil pH	1	1	1	1

$*N_{10}$ and N_{20} = number soil cores required to estimate mean within 10 and 20% of the true mean respectively (values outside 2σ are not included).

It is important that the composite bulk sample should consist of cores of constant depth and similar volume. This can be best achieved by sampling with augers or tube samplers. Sampling depths used in different calibration studies have varied. Usually the surface 7.5 or 10 cm depths have been used, but sometimes the 0-15 cm depth has been adopted (see Tables 3 and 4). Sampling depth must be considered when comparing soil test criteria.

Plant tests: Detailed procedures for sampling plants have been summarised recently (13). It is clear that for some plants further studies are required to establish suitable sampling protocols.

Criteria for selecting suitable testing procedures

Soil testing is used principally to predict fertiliser requirements of crops and pastures before planting. Plant analysis is employed mainly for diagnosing current nutritional adequacy or stress. Both types of testing have been used to monitor the residual behaviour of previously applied nutrients, and to map the regional distribution of nutrient deficiencies.

Ideally effective tests should possess most of the following attributes: (i) sampling must be relatively easy to perform, (ii) the analytical procedures should be sensitive, rapid and adaptable for routine use, (iii) test criteria should discriminate consistently between nutritional deficiency, adequacy and toxicity. The degrees of responsiveness should be closely correlated with test values, (iv) soil test values either alone or in association with other site variables should be capable of estimating fertiliser requirements, or the probability of achieving yield increases to applied fertiliser.

The calibration process

Routine soil and plant tests must be calibrated against plant response. This involves establishing a relationship (see Figure 1) between the degree of nutrient sufficiency and the soil or plant tesc for each site. Variance is associated with both coordinates of each data point, and usually the relationship is less definitive in the region of transition from deficiency to sufficiency.

Critical test values are defined in the region of marginal nutrient stress (say 80, 90 or 95% maximum yield) by fitting least squares derived exponential (14) and two-phase linear functions (15) to the data or by statistically deriving data classes (16). Because of data variability critical ranges are often preferred.

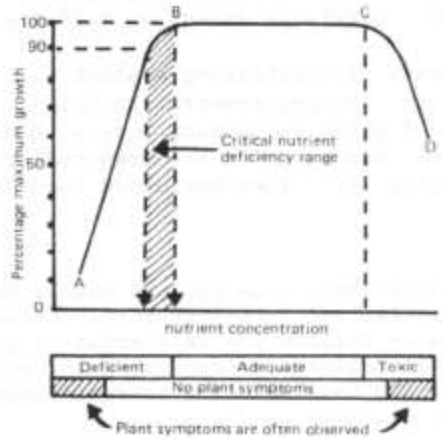

Figure 1: Relationship between plant growth and test values.

Soil tests: Traditionally two experimental approaches have been used to define soil test criteria. In the first approach, a 'diminishing returns' response surface is generated between plant yield and increasing levels of nutrient supply (preferably more than 6 levels). At each site the degree of nutrient sufficiency is estimated by the coefficients of the response surface, and then regressed against the test value of the unfertilised soil (eg 17). Sometimes the regional data are segregated on the basis of soil type or seasonal rainfall (17,18).

The second approach quantifies yield response in the presence and absence of applied nutrient. Interpretations made by this method will only be valid where the plus fertiliser treatment achieves adequate nutritional status. Test criteria are then defined by discriminating between responsive and non-responsive sites (eg.19) or by regressing actual yield increase or relative yield of the unfertilised treatment against soil test values (eg. 20,21). This is also an efficient means of confirming criteria developed by the first approach.

In both cases the field experiments are conducted on a range of soils, differing widely in nutritional status or composition and often the studies cover a number of years. Other restrictions to yield should be eliminated in these experiments (eg. pests, other deficiencies etc.).

The efficacy of any soil test depends on its accuracy in quantifying the level of yield responsiveness to applied nutrient (see D). Responsiveness has been calculated as relative yield (100[Yo/Ymax]), yield deficit (Ymax-Yo), both of which are not entirely satisfactory. On the other hand nutrient requirement is determined by the severity of the deficiency, by the shape of the response surface (17) and by the fertiliser cost/grain price ratio. Various mathematical functions have been proposed to define the response surface with varying degrees of success (eg. quadratic (22,23), square root (24,25,26) and polynomial (see 27)). However it is now widely accepted that the modified Mitscherlich function $Y=A(1-Be^{-cx})$(14), provides meaningful coefficients that can be related to measurable site characteristics (28,29). This mechanistic function should be used in future calibration studies, and also to re-examine existing fertiliser response data. The Mitscherlich function is now the cornerstone of fertiliser prediction models such as 'Decide'(30) 'Super-rate' (31).

Farmers are often confused where criteria for the same nutrient differ between test procedures. The release of new tests by regional testing services should be accompanied by appropriate extension activity.

Plant tests: The basic principles of calibrating a plant test are similar to those of soil testing except that the experimental technique is different. At a few very deficient sites increasing levels of nutrient are

applied. Plant yield and nutrient concentration are measured at specific stages of growth, regressed and critical values estimated (see 32).

F. Principles of soil testing

Chemists have characterised soil nutrients into defined pools, each of which have attributes of concentration, size and turn–over–rate. Effective extraction procedures should ideally reflect the soil solution activity (intensity; I), the ability of soil colloids to replenish the soil solution (capacity; Q) and the capacity of the soil solution to resist change in nutrient concentration (buffering capacity; WI).

Empirical nature of soil tests: The quantity of nutrient solubilised during extraction is usually much greater than that accumulated by a single crop, because plant roots are distributed through only a small fraction of the soil volume. In most soil test, no account is taken of the nutrient status of lower soil horizons or of the influence that soil, plant and environmental factors exert on the availability of soil nutrients and their acquisition by roots. It is interesting to note that in general the reliability of soil P tests for shallow rooted pasture legumes appears to be higher than for cereals (Table 3). Also, account needs to be taken of variations in bulk density between soils by either comparing soil test values on a volumetric basis or by adjusting values to constant density.

Sometimes poor correlations exists between soil tests and yield responsiveness and between soil test and predicted fertiliser requirement. Given the vagaries of seasonal conditions and their marked effects on grain yield the predictions can be expected to be imprecise in some years, but may be more reliable in irrigated crops where soil moisture is non–limiting. At best soil tests distinguish soil nutrient status into broad categories, and are only one factor used in estimating fertiliser needs.

Specific soil tests:

Soil pH: Soil pH should be measured in weak electrolytes of similar ionic strength to normal soil solutions (39). Preference has now been given to O.O1M CaC12 although 0.005M CaC12 seems more suitable for WA soils (40). However, O.O1M BaC19 has also been suggested for acidic soils (41). Nationally methods tor measuring soil pH should be standardised.

Soil acidity: The gradual acidification of many Australian soils is now recognised as a significant national problem which can result in toxicities of Al and Mn and deficiencies of P, Ca, Mg and Mo. An Australian review of this complex issue is soon to be published.

Soil tests for identifying nutritional disorders associated with soil acidity include Mo (42), Al (43) and Mn (43,44). The reliability of the soil test for diagnosing Al toxicity has been questioned because it is unable to identify the monomeric form of Al in the soil solution which causes Al toxicity in plants (45). Some of these tests will need refinements to account for the complex chemistry of acid soils of different composition.

Table 3: Comparison of selected Australian calibrations of Colwell and Olsen soil P tests for legume pastures and wheat.

Soil test	Soil depth (cm)	Pasture type *	No. sites	Critical soil P (mg/kg)	$100r^2$ or (r)	Ref.
			LEGUME BASED PASTURES			
Colwell P	7.5	1	18	24-26(90)**	81	26
	15	1	18	18(90)	NA	26
	7.5	1	21	29(85)	65	20
	10	1	25	ND	(0.17)	21
	10	1	27	~ 20	ND	33
	10	2	12	32-41(90)***	~82	24
	10	3	33	~ 30	(0.74)	23
	10	3	17	22-28(70)	65	34
	7.5	1,3	50	22-48(90)	NA	29
Olsen P	10	3	33	~10	NA	23
	10	1	42	~15(95)***	39	35
			WHEAT			
Colwell P	15	-	157	ND	26	22
	7.5	-	27	30	(~0.5)	36
	10	-	358	22-44	NA	37
	7.5	-	48	57(90)	36	28
	7.5	-	57	53(90)	19	17
	10	-	44	25(90)	34	38
Olsen P	7.5	-	57	21(90)	23	17
	10	-	44	25(90)	14	38

* Pasture type: 1 = Subclover; 2 = annual medic; 3 = white clover.
** Data in brackets are % max. yield used to derive criteria.
*** Criteria as kg P/ha 10 cm.

As liming is the most favoured method for ameliorating soil acidity reliable estimates of lime requirement are also needed. These should be developed and calibrated using several soil test parameters that are closely associated with soil acidity.

Soil N and S: The importance of maintaining adequate N and S levels in Australian soils has increased with higher cropping intensities and the greater use of high analysis fertilisers which have low S levels.

Most commercial testing services now offer clients the organic C test because it is a cheap and simple method for estimating soil organic matter. It is usually highly correlated with total N and S levels in soils of similar composition and location. However, the organic C, total N and S tests are not usually used to predict fertiliser requirement because of the complex behaviour of these nutrients in the root zone.

Many laboratories routinely analyse for NO3, NH4 and SO4 in surface soils, but the predictive value of these tests is doubtful (eg. 26,46), although their reliability is improved if sampling depth is increased (46,47).

The digestion of soil in hot KC1 is a new and rapid method for estimating potentially mineralisable N (48). The applicability of this procedure for estimating mineralisable N and S in soil should be examined.

Soil P: Soil P tests are widely sought by farmers, and several tests are used routinely within Australia (see A). The criteria and reliability of each test varies with soil type, and crop type (Tables 3 and 4).

Table 4: Criteria and efficacy of various soil P tests for wheat grown in three regions of NSW (17,28,38).

Soil P test	NW – NSW CL *	NW – NSW $100r^2$**	Central NSW CL	Central NSW $100r^2$	Sth. NSW CL	Sth. NSW $100r^2$
Bray 1	29	49	32	24	34	33
Bray 2	33	64	45	35	49	24
Truog	33	54	30	32	12	46
Lactate	17	72	18	50	9	43
Olsen	ND	ND	21	23	25	14
Colwell	57	36***	53	19	25	34
Soil depth (cm)	7.5		7.5		10	
No. sites	48		57		44	

* CL = critical soil P (mg/kg) at 90% max. yield. ND = not determined.
** $100r^2$ = % variance accounted for in relationship between relative grain yield and soil P test.
*** $100r^2$ increased to 63 where PBC included with Colwell P data.

The reliability of standard tests for characterising the P status of soils has been questioned in several studies (18,22,25), although some acceptable relationships identify broad classes of soil P status. Uncertainty is also introduced by seemingly minor changes to laboratory procedures which result in significant changes to soil test values (49). The presence or absence of mycorrhizal associations with plants (50) may also disturb the relationship between soil test and yield responsiveness to applied P.

The relationship between soil P test and fertiliser P requirement is more tenuous, since other site and economic factors need to be considered (see H). Holford and his collegues (17,28,38) have re–emphasised proposals made in earlier WA research (35) that fertiliser P requirement is influenced by both the severity of the deficiency and the curvature in the relationship between yield and P supply (respectively estimated by the B and C coefficients of the Mitscherlich function). The C coefficient is partly influenced by P buffering capacity (PBC), which when characterised improves the precision of the estimated fertiliser requirement: eg. up to 75% of the variability was accounted for in the lactate test. Previous research with subterranean and white clover pastures supports this proposal (29,35). PBC values for typical regional soils should be included in fertiliser prediction models.

Soil K: Extractants containing NH4+ or Na+ are used to desorb exchangeable soil K. Good correlations exist between both testing procedures (51), and regional criteria have been established (eg19). In several laboratories the Colwell P extract (0.5M NaHC01) is also used to determine exchangeable K. In NSW 0.01M BaC19 is also used as a K extractant, but routine determinations of non–exchangeable K (52) are no longer used. It should be noted that high K levels exist in urine patches which can exacerbate within–paddock variability.

Trace elements: Soil tests for trace elements have been reviewed recently (59). This review emphasised the need for greater standardisation in testing procedures and for more calibration data. Since this review tests for Cu (53) and Mo (42) in wheat, for Zn (54) in sub clover and B in lucerne (55) have been reported. A soil test for detecting B toxicity in sub soil horizons has also been proposed (56). Tests for Mn and Fe are often unreliable as their availability to plants is affected by soil redox reactions.

Universal extractants: Sometimes the nature of high–volume routine testing demands the use of one extractant for several nutrients. For example a 'universal' soil testing extractant (gH4H CO_3 - DTPA) is being evaluated in the USA for estimating both macro– and micronutrient status of soils using ICP technology. Criteria for existing tests will need to be modified if this procedure is adopted (57a).

G. principles of plant analysis

Plant analyses integrates soil and environmental factors which together influence the nutritional status of plants. The onset of nutrient stress first suppresses metabolic functions in plants which are then manifested in restricted growth and ultimately in the appearance of symptoms. The principles of plant analysis have been reviewed recently (32). Most plant tests diagnose the nutrient status of plants only at

the time of sampling. A few tests have been devised for predicting impending nutrient stress. In practice plant analysis is most useful for diagnosing disorders which can be corrected during the growing season. It is also used to monitor the effectiveness of current fertiliser practices (57).

Diagnosis of Nutrition Disorders

Physiological basis: Plant diagnostic tests are based on the relationship between plant growth, the supply of the nutrient under study and its concentration in plants (see Figure 1). The relationship assumes that all other environmental factors are not restricting growth. In the zone of deficiency, growth and uptake are increased as the level of nutrient supply is raised progressively, but this is accompanied by only relatively small increases in nutrient concentration. In the adequate–luxury zone further increases in uptake induce increases in nutrient concentration without affecting growth. Should uptake continue to increase, growth can be depressed by accumulations of the nutrient to toxic concentrations.

Plant symptoms: Plant symptoms are most obvious in severely stressed plants but are not always reliable for diagnosing nutrient disorders. Characteristic symptoms may not always be displayed, may be masked by multiple disorders, or complicated by stresses imposed by pests and other environmental factors. Nevertheless, symptoms remain an important tool for diagnosing nutritional stress. Their description in various species have been documented and diagnostic keys have been devised for their systematic identification (see 58).

Deficiency symptoms of mobile nutrients (N, P, K, Mg) appear first on mature aged leaves while those of immobile nutrients (Ca, Mn, B, Fe) appear on new growth and young leaves. Symptoms of the variably mobile nutrients (S, Cu, Zn, Mo) usually occur on younger leaves (58).

Chemical analysis: Tissues selected for the development of plant tests are those in which nutrient concentrations are most sensitive to variations in nutrient supply. These are usually the same tissues as those in which plant symptoms first appear. Leaves are normally selected, although stems (eg.60) and petioles are favoured for some crops and nutrients. Tests for both the total elemental composition and nutrient fractions (P O_4, SO_4, NO_3) have been developed. Examples of preferred tissues for a range 3f crops ate given in (3).

Compromises must be made on the selection of tissue for routine testing to take advantage of multi–element laboratory analysis. Usually young leaves, petioles or whole shoots are used. These compromises may reduce the reliability of the diagnoses, especially where whole shoots are used (here the analysis of older plants reflects past rather than current nutritional status) and where mobile nutrients are analysed in young leaves (here the concentration is buffered by retranslocation of nutrients from old leaves).

Plant nutrient concentrations and diagnostic criteria usually decrease with advancing plant age. Such decreases invariably occur in whole shoots because the production of dry matter exceeds nutrient accumulation. In tissues of constant physiological age the effect may be less pronounced (61): these decreases may be caused by increases in the size of the sampled tissue with advancing plant age (nutrient dilution) or by a real decrease in internal nutrient requirement. Nevertheless for interpretative purposes, plant test criteria must be related to specific stages of growth.

Nutrient analysis of grain is retrospective, but it can be used to map potential nutrient disorder on a regional scale. S deficiency in wheat has been defined by analysing N and S in grain (62).

Rapid field tests have also been developed as a means of semi-quantitatively estimating the nutrient status of growing plants (60,63). However they are not yet available commercially.

Biochemical indices: It can be argued that the chemical composition of plant tissues over-estimates nutrient requirement at functional sites within the plant because the analysis includes a proportion of nutrient which is not being metabolised (64). Two approaches have been examined for better defining

'functional nutrient requirement' (65): rates of physiological processes or activities of specific enzymes are used as markers of nutrient stress, and related to plant nutrient concentration. For example, the measurement of chlorophyll 'a' fluorescence has been used as a physiological index of Mn stress (Figure 2). Similarly sensitive enzyme assays have been developed to define the copper (66), zinc (67), molybdenum (68) and phosphorus (69) status of plants. The isolation of antibodies for these enzyme proteins is presently being examined as a means of rapidly screening the nutritional status of plants by immunological techniques (K. Peverill, pers. comm.).

To date biochemical tests have not been used in commercial diagnostic services. Problems of preserving tissues during transport to testing laboratories need to be resolved.

Prognosis of Nutritional Disorders:

Farmers expect that plant tests should detect current as well as predict future nutritional requirements. Put simply the farmer concern is: 'the present tests show my crop has adequate nutrition, but will this remain so!' Unfortunately, prediction needs to account for many factors which affect both nutrient supply and plant growth after samples are collected. Criteria derived from relationships between leaf nutrient concentration and subsequent yield are site specific and may not necessarily provide consistent prognostic criteria. Few prognostic criteria have been published, and greater emphasis should be given to their development.

Two prognostic approaches have been used. Firstly, 'safe' levels of nutrients in plants have been established which discriminate between nutrient deficiency and adequacy, irrespective of the rate of decline in nutrient concentration with plant age (70). Secondly, specific tissues can sometimes be identified as pools from which nutrients are mobilised to remote functional sites irrespective of variations in nutrient supply during growth (eg. 64).

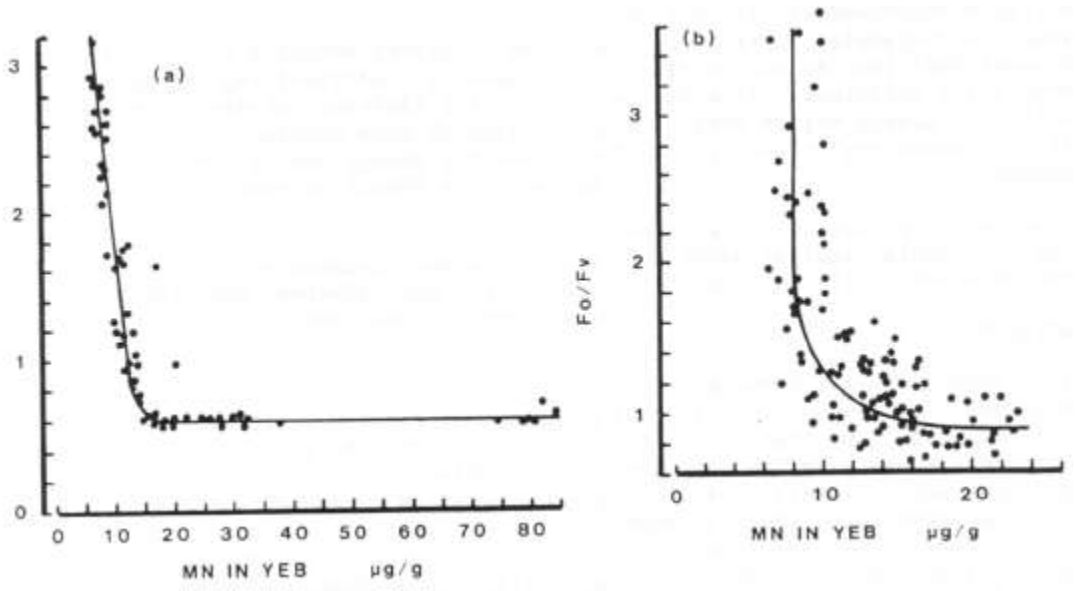

Figure 2: Relationship between Mn concentration in the youngest emerged leaf blade (YEB) and fluorescence from YES of growth room (a) and field (b) grown barley (65a).

H. interpretation and fertiliser advice

Soil testing: The principles discussed here refer to P, and to some extent can be extrapolated to other nutrients.

The 'balance sheet' approach is the simplest method for estimating fertiliser P requirements. Soil tests characterise the P status into broad classes, and fertiliser rates are decided largely on the basis of nutrient removal by crops. The advice may be modified to account for soil type, expected yield goals (which estimates grain nutrient removal), previous fertiliser history and rotation, and sometimes aspects of farm cash flows. The advice so generated relies heavily on local adviser experience, and is usually subjective. It has worked well in grazing areas of SA (33).

Fertiliser prediction models such as 'Decide' and 'Superrate' are more complex, but are objective. All available regional experimental data are assembled and appropriate relationships are determined between response surface coefficients and significant site (eg. soil tests) and environmental variables. Importantly, current fertiliser costs and grain prices are included in order to maximise profit. Management alternatives can be considered via 'what if' statements where site specific options are sought. Before being introduced the model must be validated.

The evolution of the 'Decide' model and its application in other models continues to have a decisive effect on fertiliser decision making in Australia. Some States still await its introduction. Its use in the

grazing industries pose greater problems than for arable agriculture, because of the intractable problem of relating pasture yield to financial returns from animal products. In the future models are needed to facilitate fertiliser advice for combinations of macronutrients. Models to predict lime requirement are also needed.

Plant testing: Plant tests indicate the degree of nutrient sufficiency, but have not been used to predict fertiliser requirement. Many diagnostic criteria have recently been published (3).

Multiple deficiencies will not be detected in plants severely stressed by single deficiencies, toxicities or environmental conditions (eg. drought). Several deficiencies can be diagnosed where the limiting nutrients are moderately deficient. Also the concentration of some nutrients in severely deficient plants may be greater than in healthy plants due to the 'Piper-Steenbjerg' effect (71). Diagnosticians should be aware of this anomaly.

Diagnostic criteria for specified tissues can vary between plant species, but are usually similar among cultivars of the same species. Nevertheless, the external fertiliser requirements of genotypes may vary (72).

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