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Factors affecting the interpretation and adoption of plant analysis services

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Summary. A review of the factors affecting the interpretation of plant analysis is presented. The development of plant test criteria is discussed in relation to plant part and age, seasonal nutrient changes, diurnal trends, Piper–Steenbjerg curvature, nutrient interaction and ratios, plant genotype, and environmental and crop management factors. The value of both diagnostic and prognostic plant tests is reviewed with specific emphasis on the role of prognostic tests in farmer decision making. Rapid sap testing is discussed in relation to development, utilisation, and role in agriculture. Factors affecting the utilisation of plant testing are reviewed. Within Australia the use of plant analysis services is low. Reasons for this low adoption and methods by which usage can be increased are discussed.

Introduction

The concepts and principles associated with interpretation of plant analysis were reviewed by Smith (1986). He points out that with modern equipment there is scope for increasing plant analysis services. Moreover, during the 1970s and 1980s, scientists developed many new plant tests, extending the range of species and situations in which plant analysis can be used. Research has also raised new questions regarding interpretation of plant analysis data, stemming largely from studies on changes in critical nutrient criteria in different plant parts over time.

We wish to highlight some of the factors that are important in developing plant tests and interpreting plant analyses. More importantly, we wish to look at the adoption or lack of adoption of plant testing services by the farming community and to suggest ways in which the science can be used more widely and effectively.

Development of plant test criteria

One of the basic requirements for the interpretation of plant analysis is the availability of reliable critical criteria. The development of these criteria has involved the establishment of nutrient response experiments, in which the concentration of a nutrient measured in the whole plant or a specific part of the plant is related to a yield parameter. Total nutrient has been used in most tests; however, there are examples of tests where fractions of a nutrient (e.g. sulfate or nitrate) have been measured. Other independent variables include nutrient ratios and field-based enzyme assays. Although yield is the most common dependent variable, other parameters such as quality of product [e.g. 'hollow heart' in peanut seed caused by boron (B) deficiency or 'marsh spot' in field peas resulting from manganese (Mn) deficiency] can be used. The generalised relationship follows that shown in Figure 1. Critical nutrient concentration has been defined as the concentration at which a 10% reduction in maximum growth is measured (Ohki 1977). However, there may be instances where the loss of 10% production is unacceptable, and as such the critical nutrient concentration should be determined at maximum yield. Such examples could be in high value horticulture or viticulture crops where the loss of 10% production would far outweigh the cost of the nutrient required to produce this extra yield.

Figure 1 represents the ideal situation, and in the field or glasshouse, the relationship is not always this precise. Examples of typical variability can be seen in a series of relationships taken from published papers (Fig. 2). The relationship shown in Figure 2*a* (McFarlane 1989) is well defined and is what scientists aim for in the field, while the curves shown in Figure 2*b,c* (Graham *et al.* 1985) have not reached maximum yield. Another common problem is the Piper–Steenbjerg effect, illustrated in Figure 2*d* (Ohki 1977).

Although variation between methods exists, scientists have defined critical nutrient concentrations by a number of methods (Smith 1986). The determination of these critical concentrations from data has been made either by

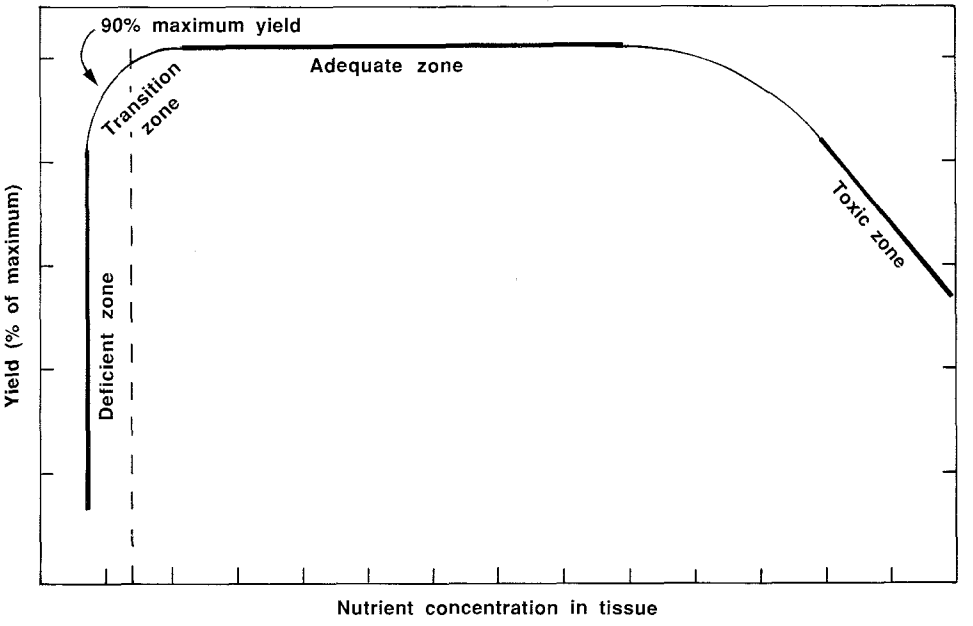

Figure 1. Typical curve for the derivation of a critical nutrient concentration in plant tissue (Smith 1986). The critical concentration is indicated by the vertical dashed line.

a simple hand-fitted curve or by applying a mathematical model. Because of a data set with little variability (Fig. 3), Reuter *et al.* (1982) were able to estimate critical zinc (Zn) concentrations of 12–14 mg/ha in the youngst open leaf (YOL) of subterranean clover by hand fitting a line. When hand-fitted curves are applied to more variable data (Marcar and Graham 1986; Fig. 4), derivation of the critical nutrient concentration as a single value implies greater accuracy than the data warrant. Therefore, we suggest that unless the data are of an excellent fit (Fig. 3), a model should be fitted. The Mitscherlich model has been used by many workers with reasonable success (Ware *et al.* 1982); however, not all data fit the typical Mitscherlich curve. A deficiency of this model is its failure to produce any measure of variability of the critical concentration, but it does produce a measure of the fit (i.e. $100R^2$ values). Cate and Nelson (1971) proposed a model that partitioned data according to goodness of fit ($100R^2$) into responsive and non-responsive groups. Although quite useful, it suffers the same problem as the Mitscherlich model (i.e. no error measure of the critical concentration). Models where the critical concentration is produced along with its error offer the best estimate. Such models have been produced by Smith and Dolby (1977) and Johansen (1978). Irrespective of the model, the critical criteria derived will be of little value if the data used are very variable.

Once a measure of the critical nutrient concentration is obtained with its associated error, we propose that a critical nutrient range be developed. The use of a critical range recognises that a single critical nutrient concentration is difficult to establish experimentally (Dow and Roberts 1982), that variability is inevitable in field samples, and that, therefore, a degree of uncertainty surrounds recommendations made when nutrient concentrations fall in that range. A critical range provides an upper concentration above which the nutrient is adequate and a lower concentration below which deficiency can be expected. When a concentration falls within the range, the farmer can be advised that the nutrient concentration is marginal and that future fertiliser management programs should take this into account. Examples of the development of critical nutrient ranges are given by Lewis and McFarlane (1986) and McFarlane (1989).

With most nutrients, the critical criteria developed for different plant species decline with plant age. In general, this occurs to a lesser extent in young tissue, but nevertheless, many papers have reported different critical criteria for different growth stages (Reuter and Robinson 1986). In an attempt to overcome this, CSBP and Farmers, the major fertiliser company in Western Australia, developed standard concentration curves for different nutrients in a range of plant species (Browne 1987). These curves relate plant weight, used as a measure of plant age, to nutrient concentration in the whole shoot. Nutrient sufficient and deficient curves are

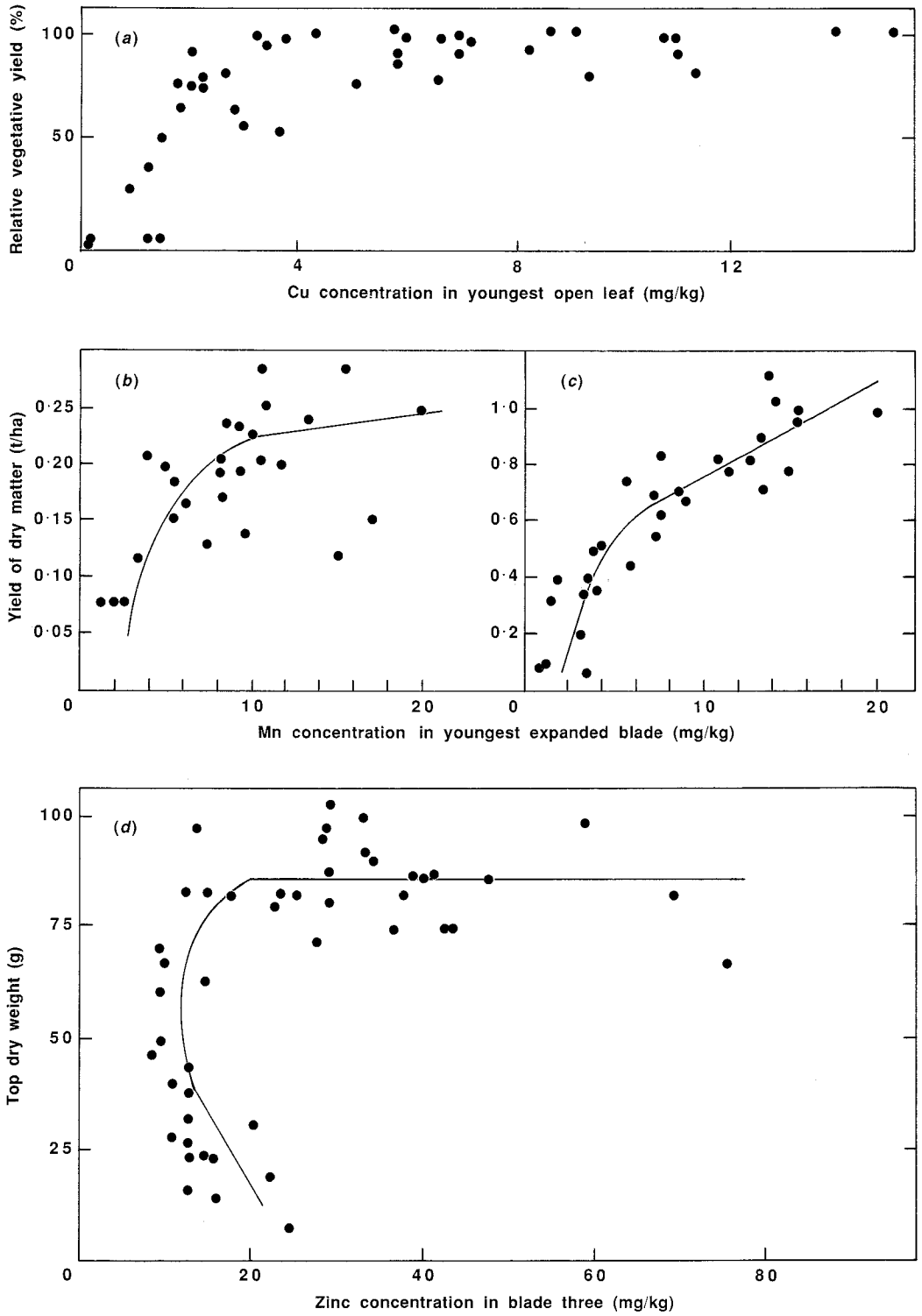

Figure 2. Examples of relationships between yield and nutrient concentrations in leaf (*a*) showing good definition of critical concentration (McFarlane 1989); (*b*, *c*) not reaching maximum yield (Graham *et al.* 1985); (*d*) with Piper–Steenbjerg effect (Ohki 1977).

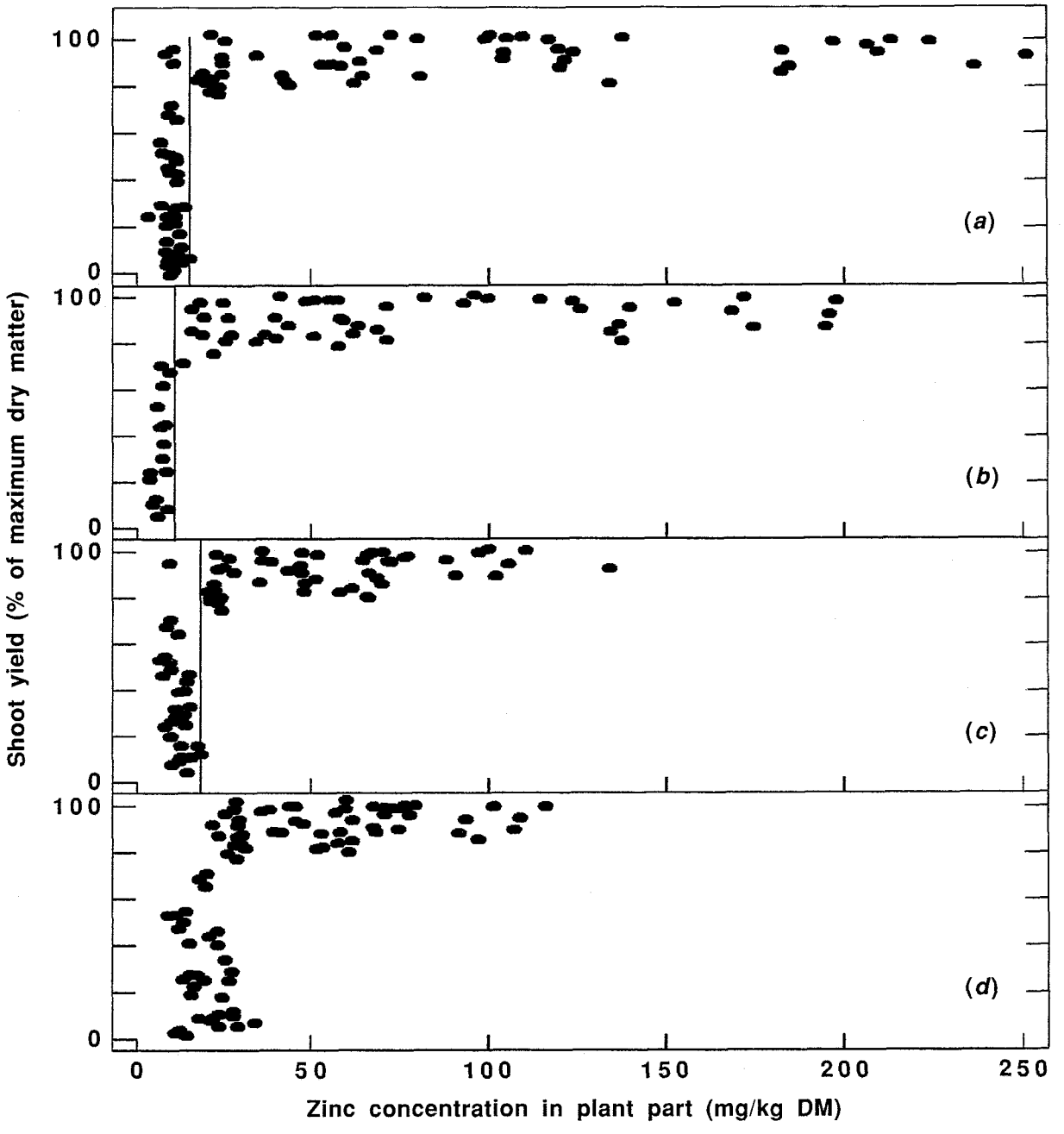

Figure 3. Hand-fitted estimate of critical zinc concentration (Reuter *et al.* 1982) in (*a*) whole shoot, (*b*) youngest open leaf, (*c*) youngest folded leaf, and (*d*) new growth. Vertical solid line indicates the critical zinc concentrations.

produced for the different nutrients. An example of copper (Cu) curves for both wheat and barley is given in Figure 5. Browne (1987) noted that the curves produced for trace elements were influenced by nitrogen (N) nutrition, and as such, N to plant weight adjustments were made. Similarly, N. A. Maier (unpublished data) has produced nutrient curves for potato petioles (Fig. 6). We suggest that this method of presentation will improve the understanding of plant analysis by the general farming community. In this way, farmers can be encouraged to monitor the nutritional status of their crops over all, or part, of the growing season.

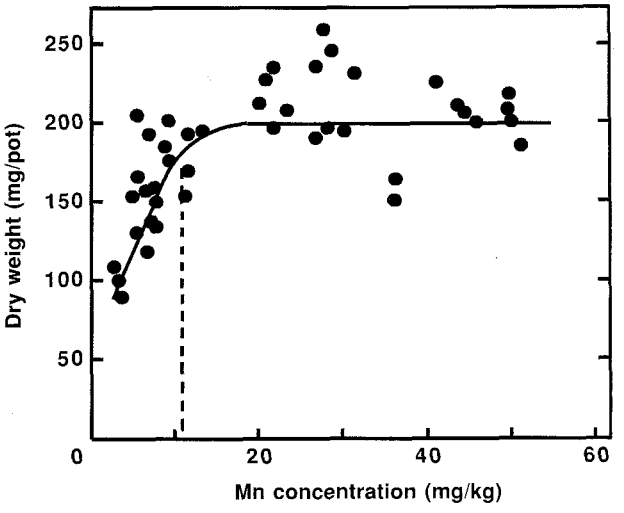

Figure 4. Hand-fitted estimate of critical manganese concentration (Marcar and Graham 1986).

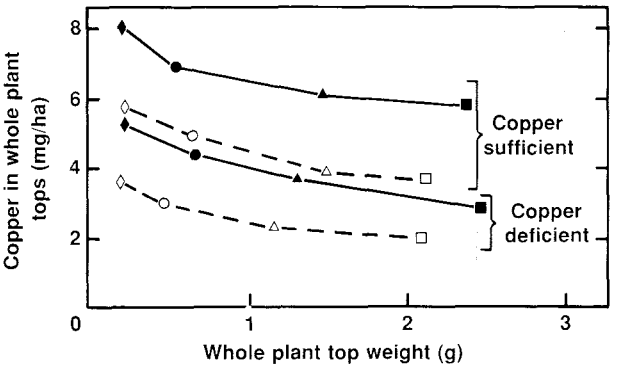

Figure 5. Standard concentration curves for copper in barley (solid symbols) and wheat (open symbols) using whole shoots (Browne 1987). Measurements after seeding are at 3 (◇,◆), 7.5 (○,●), 10.5 (△,▲), and 13.5 (□,■) weeks.

Interpretation in relation to diagnosis and prognosis

Both diagnostic and prognostic plant tests have been reported for a range of nutrients in different species. Diagnostic tests are those developed at a specific growth stage of a plant by defining the relationship between nutrient concentration and a measure of yield or quality at that point. As such, they indicate the plant nutrient status at the time the samples were taken. These tests are more accurate and are essential when a rapid diagnosis of plant nutritional status is required. On the other hand, prognostic tests attempt to assess plant nutrient status later in the growing period. In general, they have been developed by measuring nutrient status of a plant early in the season and relating this to yield or quality obtained much later. This type of plant test is more difficult to

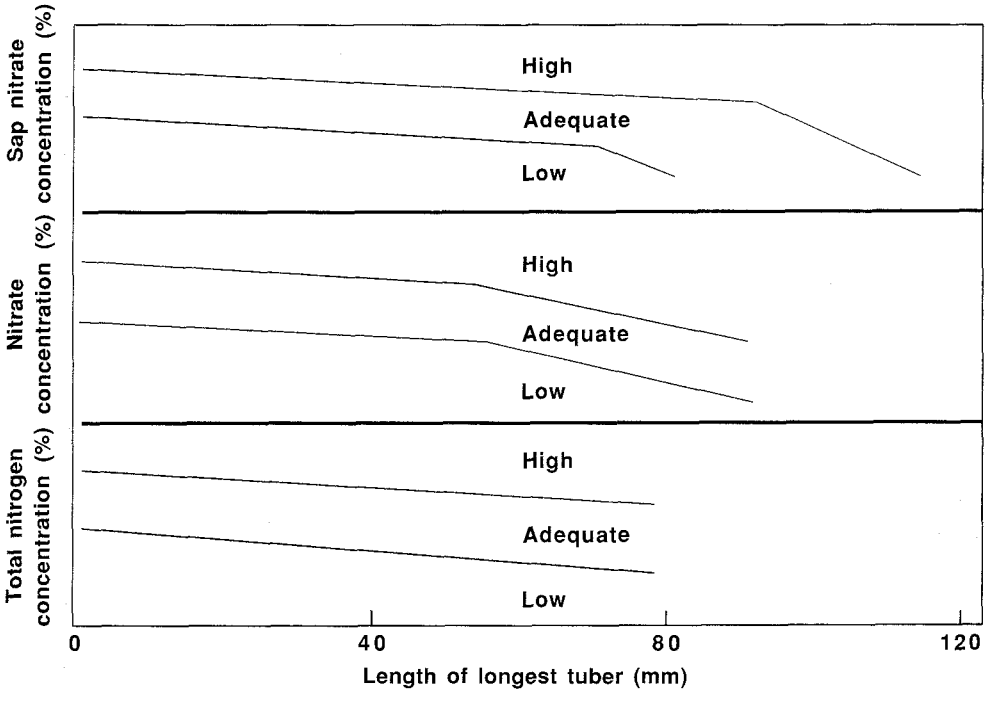

Figure 6. Concentrations of sap nitrate, nitrate nitrogen, and total nitrogen plotted against tuber length in Atlantic potatoes (N. A. Maier unpublished data).

interpret due to variation caused by factors that affect plant growth. Within the literature, final yield has often been used with success as the dependent variable (Hannam *et al.* 1985; Lewis and McFarlane 1986; Maier 1986; Pinkerton 1991; Lewis 1992; Riley *et al.* 1992). However, difficulty has been reported in relating final plant yields to a single nutrient concentration obtained earlier in the growing season (Bolland 1991).

Although there may be reasons why prognostic testing should not be used, it is our belief that farmers can gain specific practical information from plant analysis used in this way. The critical requirement for particular nutrients may be increased, but we believe this is necessary if acceptance of plant testing is to be increased.

Factors affecting interpretation

In this section we examine the factors that need to be considered when interpreting critical nutrient concentrations, and factors that may change the concentration of a specific nutrient in a plant. Some of these changes may occur for a short time, while others may last longer. It is important that these factors are understood by those interpreting plant tests.

Plant part

Many plant parts, ranging from whole shoots to key index tissues (e.g. whole leaves, petioles, blades), have been used to calibrate plant tests (Bouma 1983). For reliable interpretation, the plant part chosen should (i) be sensitive to variations in nutrient supply; (ii) show a sharp transition between deficiency and adequacy; (iii) be easily identifiable to minimise sampling error; and (iv) show a close correlation between its nutrient concentration and plant response.

The effect of sampling leaves next in age to the index leaf or youngest fully expanded leaf (i.e. YFEL−1 or YFEL+1) on nutrient concentrations and, therefore, on interpretation can be significant, depending on the species (Bell *et al.* 1987, 1990; Clark and Gourley 1987; Cresswell 1989; Dole and Wilkins 1991; Lewis 1992). Emphasis should be given to studying the effect of leaf age or position when calibrating plant tests.

Because of the difficulty in selecting and collecting young tissue from some plants (e.g. small leaf annuals), it may be more convenient to collect whole shoots. As discussed in the previous section, CSBP and Farmers have used this approach. However, the use of whole shoots to diagnose the nutrient status of annuals has been criticised on the grounds of (i) loss of sensitivity; (ii) frequent occurrence of the Piper–Steenbjerg effect; and (iii) declining critical values with increasing plant age (Smith 1986; Hannam and Reuter 1987; Lewis 1992).

In selecting the part of the plant to use, a balance between accuracy and practicality must be found; for example, it is of little value stipulating that farmers collect 400 YOL from subterranean clover if this is unlikely to be undertaken in the field. On the other hand, if whole shoots were used, then a broadening of the critical nutrient range may be necessary or a much narrower sampling time or growth stage enforced. It will be necessary to reassess the value of much of the whole shoot data to plant testing.

Plant age

The literature contains many examples of critical nutrient concentration measured in whole shoots decreasing with plant age (Smith 1975; Moody and Edwards 1978; Greenwood *et al.* 1980; Reuter *et al.* 1981; Scaife and Turner 1983; Smith 1986; Lewis 1992). There are also many examples of decreases in recently matured plant parts (Spencer and Chan 1981; Mason and Wilcox 1982; Homenauth *et al.* 1986; Elliott *et al.* 1987; Fox *et al.* 1989; Knowles *et al.* 1991; Maier *et al.* 1992).

In general, the rate of decline of critical nutrient concentration with plant age is more pronounced in young tissue for nutrients such as N, phosphorus (P), potassium (K), and sulfur (S) than for the trace elements, for which decreases with plant age have been negligible (Reuter *et al.* 1981; Robson *et al.* 1984).

It is our belief that decreases in critical nutrient concentration as plants age pose the biggest problem in plant analysis interpretation.

Seasonal trends

Significant seasonal variations in the nutrient composition of index tissues have been reported for many perennial crops: apple (Graley 1982; Tagliavini *et al.* 1992), custard apple (George *et al.* 1989), kiwifruit (Cresswell 1989), grapevine (Robinson and McCarthy 1985; Skinner *et al.* 1987), macadamia (Stephenson *et al.* 1986), pecan (Diver *et al.* 1984; Cresswell and Wickson 1986), sweet cherry (Sanchez-Alonso and Lachica 1987). For these species the preferred sampling time is when the rate of change in nutrient concentrations is minimal.

Diurnal trends

Iversen *et al.* (1985) and Coltman (1987*a*) concluded that for nitrate-N, the time of day that the sample is collected should be standardised, since large diurnal changes in nitrate-N concentrations can occur. The changes in diagnostic or prognostic criteria due to increasing plant age and seasonal and diurnal trends highlight the need to define sampling time very carefully to ensure correct interpretation. Spencer and Chan (1981), Pinkerton (1991), and Maier *et al.* (1992) emphasised the need to relate diagnostic standards to phenological stage rather than chronological age.

Piper–Steenbjerg curvature

The Piper–Steenbjerg effect as seen in Figure 2*d* has been reported for a wide range of nutrients and crops. Recent studies include P (Jones *et al.* 1972) and

copper (Cu) (Reuter *et al.* 1981) in subterranean clover; S and N to S ratio in wheat grain (Randall *et al.* 1981); P (Spencer and Chan 1981) and nitrate N (Hocking *et al.* 1984) in sunflower; and total N in onions (Maier *et al.* 1992). Earlier studies have been reviewed by Bates (1971). The establishment of reliable diagnostic standards is complicated by the occurrence of the Piper–Steenbjerg curvature, and reliance on plant test data alone can lead to serious errors of interpretation.

Because the effect is associated with acute nutrient stress, an inspection of the crop for characteristic symptoms of nutrient deficiency when collecting the tissue sample should reduce the risk of incorrect interpretation. Further, Scaife and Burns (1986) argued that in commercial field crops the severe deficiency required for Piper–Steenbjerg curvature is unlikely to occur, and as such the occurrence of the Piper–Steenbjerg curvature alone should not be used to reject otherwise useful plant tests.

Nutrient interaction and ratios

Interactions occurring between nutrients have been reviewed by Jarrell and Beverley (1981), Robson and Pitman (1983), and Black (1992). A wide range of specific and nonspecific interactions between nutrients can affect critical concentrations, induce deficiencies or toxicities, and modify growth response, depending on nutrient supply. When diagnosing nutrient disorders, interactions between nutrients within the plant should be considered to ensure correct interpretation. Interactions between nutrients within the plant occur either by affecting nutrient transport to the site of function [P–iron (Fe), N–S, N–Cu, Mn–silicone (Si)] or by affecting nutrient function [sodium (Na)–K, sparing effect] (Robson and Pitman 1983). The critical concentration of a nutrient can be markedly reduced as the concentration of another nutrient is increased (e.g. critical K concentrations are reduced as Na concentration increases; Smith 1974). Conversely Mn toxicity can be reduced by Si.

Nutrient ratios, in particular N to S, have been used with success as diagnostic indices (Spencer *et al.* 1977, 1984; Freney *et al.* 1978; Jones *et al.* 1980). However, Smith (1986) argues that where there is no apparent physiological basis for the ratio (e.g. P to N), it should not be used. The use of ratios of inorganic and total nutrient (e.g. sulfate-S/total S) has been suggested (Jones *et al.* 1980) but this has been criticised by Scaife and Burns (1986) on the grounds that the ratio will be less sensitive than either of the measurements alone and that the determination involves twice the analytical work.

Plant genotype

There are major differences between genotypes, cultivars, clones, etc. within plant species for uptake, translocation, and accumulation of nutrients (Clarke 1983). Differences in nutrient accumulation and critical nutrient concentrations between cultivars have been reported for annual and perennial species; for example, Cu in subterranean clover (McFarlane 1989); Mn (Marcar and Graham 1987) and N (Donahue and Brann 1984) in wheat; K in cotton (Cassman *et al.* (1989); P (Janat 1990) and N, P, K, calcium (Ca), and chloride (Cl^-) (Robinson and McCarthy 1985) in grapevine; K, magnesium (Mg), Ca, Fe, and Zn in lemon (Intrigliodo and Starrantino 1988); and N, P, K, Ca, Mg, Fe, and Cu in apple (Tagliavini *et al.* 1992). Conversely, Reuter *et al.* (1983) found no differences in critical Cu concentration between a range of subterranean clovers.

Leaf nutrient composition can also be affected by choice of rootstock; for example, leaf N, K, and Cl^- concentrations in grapefruit (Bevington and Cullis 1990); Ca in apple fruit (Terblanche *et al.* 1980); leaf N, K, Ca, and Mg concentrations in apple (Tagliavini *et al.* 1992); and leaf N, K, Ca, Mg, Cu, Mn, and Fe concentrations in Orlando tangelo (Fallahi *et al.* 1991).

Environmental and crop management factors

In the derivation of critical criteria, the aim is to have only 1 limiting nutrient and to eliminate other environmental and management factors. Although this may be possible under controlled experimental conditions, it may not be the case when a farmer selects tissue from the field for analysis. It is not possible to understand fully the effects that these factors may have on a given nutrient concentration, and as such, most plant-testing services recommend that tissues not be taken when the plant is under stress. However, this is not always possible, and we wish to emphasise some of the factors that may affect the interpretation of a result.

Root and air temperature. The importance of air and root temperature to nutrient concentrations has been demonstrated for many agricultural and horticultural greenhouse crops. Specific instances are cited where temperature has affected plant nutrients, resulting in deficiencies (Sonneveld 1987) and toxicities (Marsh *et al.* 1989).

Irrigation and moisture stress. Type of irrigation (e.g. overhead *v.* undertree, sprinkler *v.* drip or trickle) and frequency of irrigation and water quality (salinity) have significant effects on plant nutrient status (Ojala *et al.* 1983; Stark *et al.* 1983; Feigin 1985; Cerda and Martinez 1988). For some nutrients, different critical concentrations have been reported for prognosis of deficiency in irrigated and non-irrigated crops. For example, Swaider *et al.* (1988) reported critical nitrate-N concentrations in petioles of pumpkin at early fruiting of 4000 mg/kg for irrigated and 8000–8400 mg/kg for dryland. The relationships between relative marketable

yield and petiole nitrate were less precise for dryland (R^2 = 0.34–0.35) than irrigated (R^2 = 0.80) crops. This example shows the importance of calibrating plant tests under a range of cultural conditions and the problem of calibrating reliable plant tests for non-irrigated crops where adverse environmental conditions (e.g. transient moisture stress) affect the relationship between nutrient concentrations and yield response.

Herbicides. Recent studies in Western Australia (Robson and Snowball 1990; McLay and Robson 1992; Osborne and Robson 1992) and South Australia (I. D. Black and N. Wilhelm pers. comm.) have shown that the application of sulfonylurea herbicide (e.g. chlorsulfuron, metsulfuron-methyl, triasulfuron) can reduce uptake of Cu and Zn in wheat, and P and Zn in barley. In wheat, Cu and Zn deficiencies can be induced by the application of sulfonylurea herbicides if supplies of those nutrients are marginal for growth (Robson and Snowball 1990). Because many cereal crops are treated with these chemicals early in the growing season, it is important that research is maintained in this area to understand the interactions. How long the effect of reduced uptake remains and the effect of soil type (e.g. pH) are just 2 issues that need to be addressed.

Nutrient management characteristics. The nature and significance of relationships between site nutrient management and supply characteristics and critical nutrient concentration have important implications for prognosis, because for any crop, a wide range of nutrient management strategies is used. Nutrient management characteristics that affect plant nutrient concentration include the following: (i) nutrient source, e.g. KCl *v.* K_2SO_4 for K (Maier 1986), and NO_3^- *v.* NH_4^+ sources for N (Rudert and Locascio 1979; Smith 1984; Barker and Ready 1988; Patten *et al.* 1988; Barker and Ready 1989; Martinez and Cerda 1989; Knowles *et al.* 1991); (ii) placement, e.g. banded *v.* broadcast (Smith *et al.* 1990); (iii) timing or frequency of application. With regard to nutrient source, Ulrich and Cerda, in a hydroponic study with the tundra plant *Dupontia fisheri*, showed that N source [e.g. $(NH_4)_2SO_4$, $Ca(NO_3)_2$, NH_4NO_3] affected critical nitrate-N and total N concentrations in stem and blade tissues, and tissue inorganic P, total P, K, Ca, Mg, Fe, Mn, Cu, Zn, and Na. With regard to timing or frequency of application, Coltman (1987*b*), in a study with fresh market tomatoes, suggested that diagnostic standards for sap nitrate-N during the growth period may be lower when N is supplied frequently (i.e. once or more per week) than with a few, discrete applications. This hypothesis has important implications for the diagnosis and prognosis of nutrient deficiencies in horticultural crops, where the use of drip or trickle irrigation and fertigation is common.

Other management factors affecting tissue nutrient concentration include tillage (Blevins *et al.* 1986; Cornish 1987; Gates *et al.* 1981), fumigation (O'Sullivan and Reyes 1980), plant density (Mack 1983), pruning (Coltman 1987*a*), and foliar sprays (e.g. the application of fungicides or pesticides containing large amounts of mineral elements such as S, Cu, and Zn complicates the interpretation of plant test data).

Other factors. Kaplan and Bergman (1985) and Shattuck (1987) have reported that virus infection can significantly affect plant nutrient composition. For example, N, P, Mg, and Zn concentrations increased and K decreased in virus-infected rutabaga plants. The occurrence of mycorrhizal fungi can affect the mineral nutrition of many agronomic crops (Ojala *et al.* 1983).

Rapid sap testing

So far we have discussed plant tests developed by correlating total nutrient concentrations with some yield parameter. Determination of total nutrient concentrations requires laboratory facilities and is time-consuming. It is the belief of some workers that rapid field-based tests that provide quick, on-the-spot information have an advantage over laboratory analysis of plant samples in optimising fertiliser decisions (Handson and Sheridan 1992).

Development and utilisation

Although the use of sap-testing technology for assisting nutrient management of agricultural and horticultural crops appeared about 70 years ago, only in recent years has this technology been offered to the farming community. Following extensive studies of the P status of subterranean clover, Bouma and Dowling (1982) proposed a rapid plant test. As a result of this and other work, a field kit for both P and N, known as the Greenleaf Farm Lab, was released by CSIRO. Although the technology was sound, the kits have not been distributed widely because they were not considered 'user friendly' (I. Grant pers. comm.)

Laboratory-based nitrate-N sap testing using basal stems of cereals to assess N status during early tillering has been developed (Elliot *et al.* 1987) and offered commercially by the South Australian Department of Primary Industry. Again, limited use of this technology has been made by farmers due to difficult sampling procedures, slow turnaround times, and consequent missed opportunities for timely applications of N to the tested crop.

Nevertheless, the early development of this technology probably provided the technological base and stimuli for the development of the simpler on-farm sap-testing services currently being offered for specific agricultural and horticultural crops. Researchers at the Victorian State Chemistry Laboratory and Pivot Fertilisers have been developing and calibrating field tests for N, P, K, and S in cereals, oilseeds, and

horticultural crops in south-eastern Australia (Handson and Sheridan 1992).

Commercial companies have recently produced rapid nitrate-N kits (e.g. 'Nit-rate' service for cereals, Pivot Fertilisers; 'Nitraquick' test kit for cereals and potatoes, Agritec Pty Ltd). We do not intend to examine the merits of these different services; the technology is reasonably new and testing of their reliability over time will determine their life in the marketplace.

Value

It is not certain that sap testing will improve the fertiliser decision-making process on farms. Because of the simplicity of use, the adoption of sap testing by farmers may even lead to a decrease in yield. For example, farmers may induce N deficiency by delaying N fertiliser application to cereals until after a sap test, despite a clear need to apply N at seeding based on other considerations.

The promotion of new sap-testing technology should not be seen as an alternative to laboratory-based plant (and soil) testing. The most effective role of sap testing is as an aid to crop nutrient management so as to fine-tune fertiliser programs and monitor crop health.

Alternative interpretation methods

An alternative approach to the critical concentration, critical nutrient range, or sufficiency range methods of interpreting the nutrient content of plant tissue is the diagnosis and recommendation integrated system (DRIS) (Sumner 1978). The DRIS procedure recognises antagonisms and synergisms between plant nutrients and emphasises the importance of nutrient balance. DRIS norms developed for any given crop are claimed to be independent of plant age and are applicable in any environment. In Australia the DRIS procedure has been criticised, particularly on theoretical grounds, and its use has not been recommended, nor has any study been published (Robinson 1986; Smith 1986). Many overseas studies with annual and perennial crops have evaluated the use of the DRIS approach; these include lettuce (Sanchez *et al.* 1991), oranges (Beverley 1987*a*), soybeans (Beverley 1987*a*, 1987*b*; Shuman *et al.* 1992), potato (MacKay *et al.* 1987), rice (Counce and Wells 1986), apple (Parent and Granger 1989), sweet cherry and hazelnut (Righetti *et al.* 1988), white clover based pastures (Jones and Sinclair 1991), and greenhouse tomato (Caron *et al.* 1991). These comparative studies between DRIS and the critical concentration or sufficiency range approaches have been important because (i) they provide data showing the advantages and limitations of both diagnostic procedures, and (ii) they provide data on the reliability of diagnostic standards to identify limiting nutrients. For example, Counce and Wells (1986) reported yield increases in only 1 of 6 experiments by applying nutrients according to DRIS predictions. The critical concentration approach predicted N deficiencies in 10 experiments; however, in only 4 did N fertilisation increase yield. Nitrogen responses also occurred in 3 experiments in which N was not diagnosed as deficient. Results such as these are a matter of concern and they emphasise the importance of validating prognostic standards by conducting experiments at many sites over a number of years. For example, Iverson *et al.* (1985) concluded that maize stalk nitrate concentration was highly correlated with grain yield response, based on a limited number of sites and years. However, when a large number of sites and years (87 sites, 1984–87) were included, the relationship, although significant, was of little predictive value ($R^2 = 0.25$) (Fox *et al.* 1989).

Interpretation of relation to animal nutrition

In a pasture situation the final product is most commonly the grazing animal; it is therefore important to consider animal nutrition. Analysis of herbage can be used as a guide to animal performance. Instead of selecting a specific plant part, an analysis of the mixed herbage is more appropriate (Hosking *et al.* 1986).

Minson (1990) published an excellent review of the effects of forage on animal nutrition. The most discussed interaction is that between the concentrations of Cu and other plant nutrients in herbage (Suttle and McLauchlan 1976). Whereas a critical Cu concentration of 4 mg/kg may be adequate for plant growth in subterranean clover (McFarlane 1989), 5–6 mg/kg in herbage is the minimum concentration for optimum sheep growth (Langlands *et al.* 1981). The adequacy of this Cu concentration for sheep health varies with the concentrations of molybdenum (Mo), S, and Fe in the herbage. High concentrations of any or all of these nutrients will reduce Cu absorption from the ingested forage by the grazing animal.

Plant analysis can also be used to predict toxicity in pastures for grazing animals. For example, in the case of grass tetany, the ratio K/(Ca + Mg) is a guide to potentially lethal pastures. Lewis and Sparrow (1991) showed that when this ratio exceeded 2.2 in grasses, cattle deaths occurred. The critical ratio varies with plant species; moreover, grasses growing on different soil types had different K/(Ca + Mg) values.

Utilisation of plant testing

Utilisation of plant analysis by the farming community is still relatively low, prompting the need to examine critically the factors that limit adoption. The type of enterprise is clearly not an overriding consideration, since in horticulture, cropping, and grazing enterprises, farmers have been slow to adopt plant testing as a routine part of their farm management. Many people associated with the agricultural industries believe that the opportunity exists to make significant

farm productivity gains by extending the utilisation of plant testing.

That farmers fail to adopt plant testing is not necessarily a result of any weakness in the methodology itself but may be the consequence of overemphasis of the methodology and its scientific basis and underemphasis of educating the target audience to the relevance and financial benefit of timely and sound advice on nutrient management in crops and pastures.

The market

Quantitative data on the adoption rates of plant tissue testing in Australia are somewhat limited. This may be due in part to the difficulty of collating statistics from the growing number of facilities offering this service to the farming community. Nevertheless, the data available clearly show that the overall utilisation of plant testing is very low by all farming groups (Reuter and Hannam 1987). The evidence also indicates variation between States in the extent to which plant testing is used (K. Peverill pers. comm.).

The use of plant testing in horticulture currently exceeds that in broadacre cropping and grazed pastures. This probably reflects the more intensive production systems and associated high value crops with tree, vine, and vegetable production. In South Australia, Victoria, and southern New South Wales, 60–70% of corporate horticultural farmers utilise plant testing annually, whereas utilisation is in the order of <10% among smaller farmers (S. Phillips and P. Gallasch, Ag-Plus SA, pers. comm.). Although the population base is low, an estimated 60–80% of the plant samples analysed in Victoria are horticultural (K. Peverill and J. Shovelton pers. comm.).

Estimates of adoption by broadacre crop and grazing farmers, respectively, in South Australia are 3–5% and <1% annually (G. Hamdorf, Ag-Plus SA, pers. comm.). In Victoria, usage by farmers is estimated to be 1–2% for both crops and pastures. By contrast, in Western Australia usage by farmers is 8–10% annually, split 4 : 1 on crops and pastures (G. Proudfoot pers. comm.). Estimates for other States are unavailable.

Growth in the plant-testing market remains relatively slow, and an increase in the utilisation of plant testing services throughout Australia will require education and effective marketing approaches.

User characteristics

Improving information transfer will have to be an integral component of any strategy for improving acceptance and adoption. There are limited published data on farmer behaviour relative to the use of plant and soil testing in Australia. However, localised South Australian quantitative and qualitative market research into use of soil and plant testing, carried out by Adelaide & Wallaroo Fertilisers/Top Australia Ltd in 1985, 1989, and 1990, identified specific farmer behaviour characteristics and limitations to adoption (I. Grant unpublished data). Key findings included the following: (i) more productive and efficient farmers utilised plant and soil testing to improve plant nutrition and to maximise productivity; (ii) once they initiated a testing program, farmers continued to use the service on a routine or regular basis; (iii) 80% of users followed the recommendations as presented; (iv) a high percentage of farmers had a positive attitude towards testing and a strong perception of benefits, with many viewing testing as a discretionary item in farm management and using it particularly as a problem-solving device; (v) cost of testing was not a serious deterrent.

Limitations to adoption

Sample collection by farmers proved to be the single biggest barrier to adoption. Farmers admit to a non-disciplined approach and attitude to sampling even where they have a positive attitude towards testing. Farmers react positively to having this task either done for them or made easier. The task of selecting and taking numerous specific plant parts and identifying plant age, particularly in the case of leguminous pastures, is an important stumbling block.

Apart from the logistical problems, the greatest source of error arises during sampling (Hannam and Reuter 1987). As we have already discussed, a review of sampling procedures and the plant parts collected may be necessary to make sampling user friendly whilst minimising sampling error and retaining sample quality.

Some farmers perceive plant analysis as a very complicated technology and as such are not willing to use it. It is suggested that education processes be put in place to help to overcome this barrier, thus encouraging farmers to go out and sample.

The market research mentioned above identified other factors of lesser importance leading to reduced acceptance and adoption of plant testing (i.e. turnaround time too slow for remedial action; perception by farmers of commercial bias from fertiliser companies offering testing services). Efforts to maximise turnaround efficiency and to develop plant-testing credentials are progressively being upgraded by suppliers.

Conclusions

We have attempted to highlight the science involved in the interpretation of plant analyses and to show why we need to reassess how we formulate critical criteria, taking into account the variation due to a range of factors. In particular, the effect of both plant part and age on critical nutrient criteria needs careful attention. More importantly, we have illustrated the general lack of adoption of plant testing by the farming community. As

such, we suggest there is a strong need to 'sell' the benefits of the services to the agricultural industry. Advisers and farmers should clearly understand how plant testing fits into the fertiliser decision-making process. Many farmers (and some unskilled advisers) tend to take test results at face value and do not understand how to interpret them.

We believe that within Australia there is a limited number of field advisers with sound interpretation skills, and that the introduction of programs for the training of advisers is essential if the technology is to be adopted more rapidly. The ongoing development of computer- aided interpretation models will assist in maintaining consistency and quality and will improve the skills of advisers. Further, the use of computer-aided interpretation models will increase the capacity of suppliers to interpret results more rapidly. We believe there is a clear need to try to change farmer perception of plant testing from a diagnostic model to a means of long-term nutrient management of crops or pastures through regular or strategic testing programs.

Given the strong belief of both the academic and agribusiness sectors in the benefits of plant testing, and given the low level of utilisation of plant testing by farmers, there is a clear responsibility for a better understanding of the processes by which farmers learn about, accept, and adopt technology. The reluctance of farmers to exploit the potential that plant testing offers poses a significant challenge to commercial and government organisations.

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