A COMPARISON OF FOLIAR AND SOIL UPTAKE OF NUTRIENTS IN FRENCH BEAN (*PHASEOLUS VULGARIS* L.).

A THESIS PRESENTED IN PARTIAL FULFILMENT OF
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Susan Elizabeth Jolly

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ABSTRACT

An aspect of each of three factors relating to efficiency of fertilizer use were studied in glasshouse experiments using beans Phaseolus vulgaris var. Gallatin 50. These three factors were: the quantities that can be applied; physiological aspects of nutrient utilization following foliar uptake; and interactions with other sources of nutrient supply.

Distribution patterns of S^{35}, P^{32} and Zn^{65} were examined following application to soil and foliage of beans. It was found that a greater proportion of P^{32} and Zn^{65} was present in the fruit following foliar uptake than was the case following root uptake. This difference was not evident for S^{35}.

Retention of a commercial nutrient spray on the foliage of bean plants was measured and found to correlate well with both leaf area and leaf fresh weight.

The effect of sprays on leaf chlorophyll was also examined. Environmental effects were found to have more influence on leaf chlorophyll than nutrient sprays.

Root uptake of P^{32} was increased by spraying the foliage with either nutrient solution or water. It was concluded that the effect was water related and not connected with nutrient application.

The implications of the above findings were discussed in the

context of efficiency of fertilizer use.

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CHAPTER 1

INTRODUCTION

Fertilizers are an important input in agricultural and horticultural production systems. However, the increasing costs of fertilizer materials has resulted in a need for improved efficiency in their utilization. Various ways in which the efficiency of fertilizer use may be increased have therefore received considerable attention in recent years. These studies have included new fertilizer compounds and mixes, timing of applications and placement of the fertilizer. The application of fertilizer solutions to the foliage has also been considered in this context, as an alternative or supplement to conventional soil application.

Foliar application of nutrients is a technique that has been used for a number of years and in certain circumstances has become accepted practice. Examples of such circumstances include application of micronutrients to a number of crops (Murphy and Walsh, 1972), and the control of quality in fruit crops (Swietlik and Faust, 1985).

It is noticeable that cases where foliar fertilizers are regularly used are more common in intensive production such as horticulture than on less intensive types of production. This may be due to a number of factors. A high value crop will need a smaller yield increase in response to a fertilizer application for that application to be economic, than will a low value crop. Quality tends to be more important in horticultural crops than most agricultural crops, and foliar applications may affect quality even where quantitative yields are not effected. In addition, intensive production systems often have spraying facilities available and may even have regular spray programmes, into which nutrient sprays may be incorporated.

In a responsive situation, the crop response obtained from fertilizer application is the result of three contributing factors; supply, utilization and interactions. Supply includes a consideration of the quantities that can be supplied to the plant by the technique. In most cases this will be much greater for soil application than for foliar applications. However the effect of the soil on availability of the applied fertilizer must also be taken into account, and in some cases the quantities that are available for uptake may be less with soil applications because of soil interactions. An example of this is iron on calcareous soils. The quantities that may be supplied by foliar applications depends on the amount of solution retained on the leaf surfaces. Little work has been done on this with regard to nutrient solutions, however there is a considerable body of information on spray retention from work with pesticides and herbicides (for example, Innis et al., 1951).

Plant utilization in this context involves the use of the absorbed nutrients in production of the portion of the plant that forms the yield. The efficiency with which foliar and root absorbed nutrients are utilized may vary, especially if the translocation of the nutrient is restricted. A considerable quantity of earlier work focussed on this aspect of crop responses to foliar-applied nutrients (see Wittwer et al., 1963; Swietlik and Faust, 1985).

Interactions include the effect of the uptake of the fertilizer on the physiology of the plant and hence on yields. Foliar applications may affect root uptake of both the nutrient applied and other nutrients, while soil applications may affect uptake of other nutrients. This will influence the overall efficiency of fertilizer use.

The contribution of these three factors to observed crop responses to foliar fertilizers and the effect of environmental, soil and plant factors on that contribution requires more attention than it has received in previous work. This study deals with one aspect of each of these three areas in *Phaseolus vulgaris*:

(i) The degree to which foliar sprays are retained on the foliage is investigated. This aims to compare the effect of foliar absorbed nutrients with the effect of root absorption of spray runoff.

(ii) The relative efficiency with which plants utilize foliar and root absorbed nutrients in the fruit is studied, using isotopes of sulphate, phosphate and zinc.

(iii) The effects of foliar sprays on root growth and function is investigated.

CHAPTER 2

CHAPTER 2

REVIEW OF LITERATURE

2.1 Introduction

The subject of this review is the use of foliar fertilizers as compared with application to the soil. In order to understand the effectiveness of either technique, it is essential to understand the mechanisms involved in plant uptake and utilization of nutrients from either source and the ways in which they differ. The effects of climate, soil, plant and fertilizer characteristics in each case must be considered as they will alter the relative utility of the methods. Thus, this review will first discuss the physiological aspects of nutrient supply and plant utilization with application to soil and foliage. This will be followed by a consideration of the agronomic aspects of the two techniques.

2.2 Pathway of nutrient movement during uptake.

2.2.1 Roots

2.2.1.1 Supply of nutrients to the root

The first stage in uptake of mineral ions by plants is the supply of the ions in solution to the surface of the absorbing organ. In general, providing there is adequate soil moisture, there are few problems with contact between solution and the root. This means that the supply of the solution from which uptake occurs to the root surface is basically continuous with time. However the composition of the solution may vary considerably and in a complex manner, depending on a number of soil factors. Some soils are higher in certain elements than others. For example, soils that have a high mica content tend to have higher potassium levels in the soil solution as this mineral releases potassium as it weathers.

Reactions in the soil also determine concentrations in the soil solution. Phosphate undergoes adsorption reactions which contribute to the very low level of phosphate usually found in the soil solution (0.01 to 0.5 $\mu g\ g^{-1}$). The solubility of some phosphate compounds (for example apatite), is low,and so phosphate in this form will not be available for uptake. In contrast, nitrates are highly soluble and hence a large proportion of the soils' nitrate will be in solution. Composition of the soil solution also depends on electrostatic interactions between ions in the solution and the charged surfaces of soil particles. These interactions are complex and have been discussed elsewhere (Nye and Tinker, 1977).

Factors affecting these reactions will be discussed below.

2.2.1.2 Movement into and across the root

The root cortex is generally accepted to be readily accessible to the soil solution (Russell, 1977). Movement across the cortex may be either apoplastic (in the cell walls and intercellular spaces), or symplastic (in the cytoplasm of cells as connected by the plasmadesmata), or a mixture of both. This varies with the ion, for example, potassium movement seems to be largely symplastic and calcium movement largely apoplastic (Marschner, 1983). Except at very apical sections of the root, however, the apoplastic route is discontinuous at the endodermis and thus movement into the stele must involve uptake into the cells and symplastic movement into the stelar parenchyma from which release into the xylem vessels may take place, most of the transport of ions occurring in the xylem. Mechanisms of uptake by cells and release into the xylem have been discussed in detail elsewhere (Luttge and Higinbotham, 1976) and will not be dealt with here.

2.2.2 Leaves

2.2.2.1 Supply of nutrients to the leaf

In contrast to the case for roots, the supply of nutrient solutions to leaf surfaces is generally a discrete event rather than a continuous process. Thus the quantity that may be applied is an important constraint on the amount of uptake that may occur. The quantity of solution that is retained on the leaf after application of a spray will depend on both leaf and solution characteristics. Size of spray droplets can be important, smaller droplets being retained better than large ones (Merrall, 1981). Solution surface tension and leaf surface characteristics together determine the contact angle of the droplet on the leaf surface. This is the angle at which the drop meets the surface (figure 2.1). A low contact angle reduces the likelihood of the droplet running off the leaf surface. It also increases the leaf

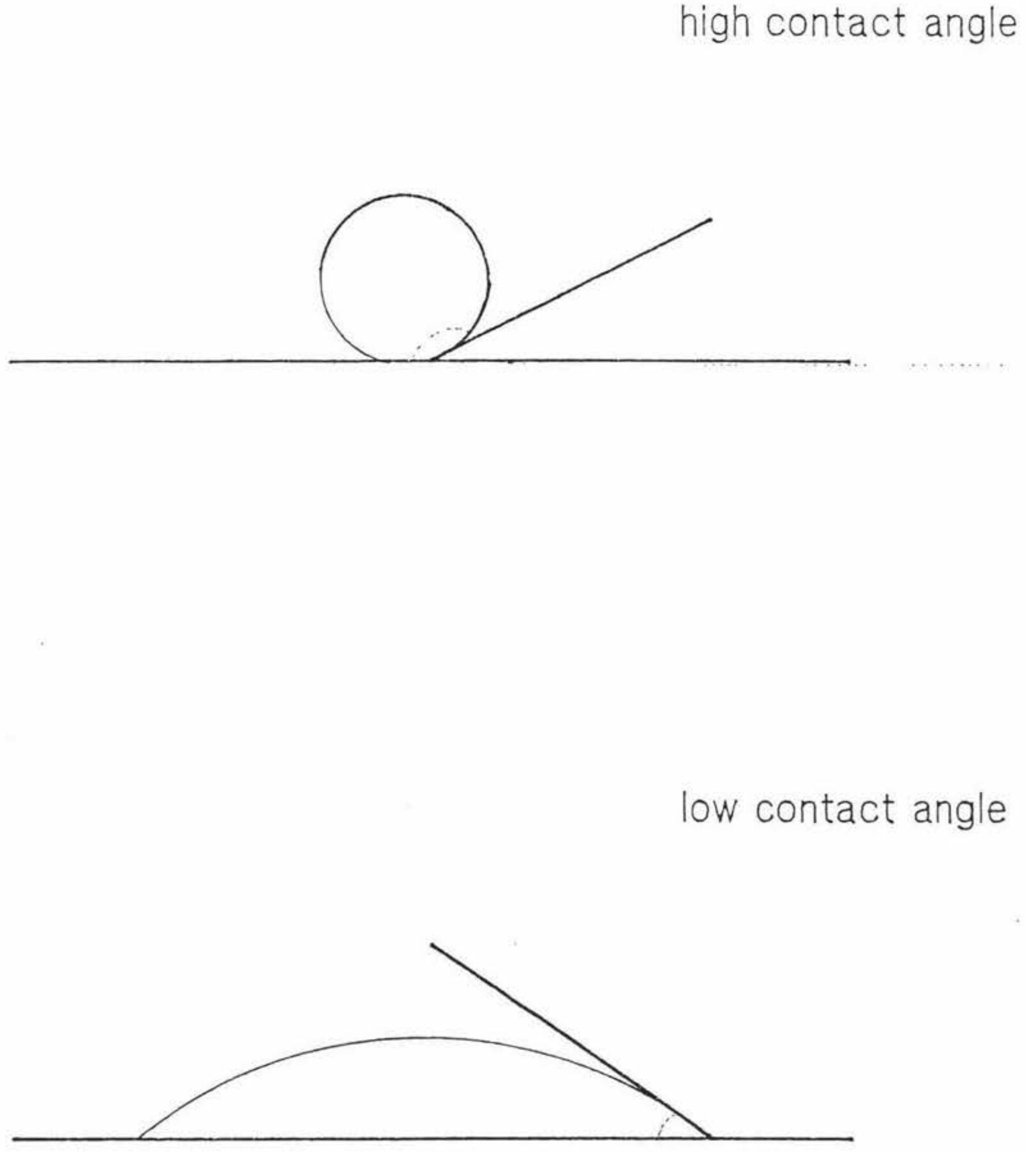

Figure 2-1 Contact angles of droplets on a surface.

area in contact with the droplet and hence the potential uptake. In agricultural situations the surface tension of the applied solution may be varied depending on the leaf surface characteristics. These mainly include the chemistry and morphology of the epicuticular waxes (Martin and Juniper, 1970), and presence of such features as hairs, trichomes and veins which affect surface roughness. Leaf angle also influences the retention of solutions. A horizontal leaf is more likely to retain a droplet than a more vertical leaf. Leaf angle also affects spray interception (Innis et al., 1951).

The other factor that affects the amount of nutrient supplied to the leaf surface is the concentration of the solution. Unlike soil supply of nutrient, the concentration and composition of foliar supplied solutions can be closely controlled. However, there is a constraint on the concentration that may be applied due to the damage that too high a concentration may cause (section 2.3.2.4).

2.2.2.2 Movement into and across the leaf

Here also, leaf uptake contrasts with root uptake as the cuticle constitutes a barrier to ion entry that is not present in the root system. The means by which water and solutes move across the cuticle is not clear, although a number of hypotheses have been put forward (Franke, 1961; Hull, 1970; Schonherr, 1976). It does seem however that the chemistry of the cuticular waxes is more important in regulating movement than is thickness of the cuticle (Martin and Juniper, 1970).

Once entry through the cuticle has been effected, pathway to the vascular system is not long, due to the effective vascularisation in the leaf. As is the case with roots, the path may be symplastic or apoplastic. Work with dyes has suggested that, in some cases at least, symplastic movement occurs (Kannan, 1986). A point that may complicate the concept of apoplastic movement is the direction of transpirational water flow. In roots, water flow would generally favour movement of ions in the apoplast towards the stele. In the leaf however, the transpirational flow, when present, will not favour apoplastic movement to the stele.

There is evidence that, in some species at least, the leaf stele may also have a suberised ring analogous to the casperian strip in roots (Lauchli, 1972) and so a similar requirement for cell uptake before transfer to the stele would also apply in these cases. The movement of inorganic ions into the phloem has received comparatively little attention, although there is evidence to support active loading in at least some cases (Lauchli, 1972).

2.3 Translocation

Following uptake into the plant, ions may either move to the vascular system as described above, or be retained in the cells of the leaf (mesophyll) or root (cortex). The extent to which the latter case occurs will vary with nutrient status of the plant and the ion in question. Some ions may be retained to a considerable extent in the root system, for example, zinc (Lindsay, 1972) especially if supply levels are high. There is also evidence to suggest that copper movement from the root may be restricted under some circumstances (Karhadkar and Kannan, 1984).

In leaves, absorbed minerals are only likely to be exported if the current requirements of the leaf are met or demands of other sinks are strong. Transport from the leaf may be restricted for some nutrients by limited mobility in the phloem, an example being calcium.

Another aspect that must be considered when dealing with translocation of absorbed minerals is the form in which ions are translocated. Most of the ions translocated from the root in the xylem are inorganic, although some micronutrients may be chelated (Tiffin, 1972). An exception to this is nitrogen. The form of nitrogen in the xylem varies with species; in some species reduction and assimilation occur largely in the root and organic forms are translocated. In other species, reduction occurs largely in the leaves and xylem transport is in the inorganic form (Pate, 1980). In the former case, uptake and metabolism in the root cells is a necessary step before release into the vascular system.

The form in which minerals move in the phloem also varies, with some, such as potassium, entirely as the inorganic ion and others,such as nitrogen, purely in the organic form (Pate, 1980). Some may be present in the phloem in both organic and inorganic forms, for example, phosphorus and sulphur (Bonas et al., 1982; Bieleski and Ferguson, 1983).

The overall distribution of mineral elements will vary during the life of a crop (see Hocking and Steer, 1983), but it is often possible to specify a physiological stage that is of particular interest, for example reproductive maturity. In general, the mobile elements will concentrate in fruit and/or storage organs, while the immobile elements such as calcium and boron will remain at the point of original distribution. Unfortunately, much of the work concerning movement patterns of ions following foliar uptake has been studied in plants during vegetative stages of growth and have not included considerations of the effects of developing fruit. Thus the effect of fruit on such patterns requires more work.

2.3.1 Root absorbed nutrients

As mentioned above, translocation of root absorbed minerals occurs mainly in the xylem. However the xylem is not solely responsible for distribution in the shoot system. Transfer of certain ions such as phosphate, sulphate and potassium from xylem vessels to the phloem has been shown to occur (Hoad and Peel, 1965; Pate, 1976) and this can result in enrichment of the phloem streams destined for areas of high sink activity such as shoot apices (McNeil, 1980). In addition there is a general redistribution of certain minerals out of mature leaves to apices, storage organs and reproductive organs. The degree to which this occurs depends on the mobility of the ion in the phloem. Thus ions such as potassium are readily redistributed from the leaf while calcium, which is virtually immobile in the phloem, is not (Biddulph et al., 1958). Some nutrients, such as zinc, are described as having intermediate or variable mobility. This means that mobility in the phloem varies with physiological conditions in the plant, in particular the supply of the nutrient (Loneragan et al., 1976).

The degree to which redistribution occurs also depends on the degree to which immobilisation in the tissue occurs. Thus phosphate may undergo continuous cycling in the plant while sulphate tends to be more quickly immobilised by incorporation into proteins in young tissue and does not undergo further redistribution (Biddulph et al., 1958).

2.3.2 Leaf absorbed nutrients.

Translocation of foliar absorbed ions could be expected to follow similar patterns to ions undergoing redistribution from leaves as described above. This in fact does seem to be the case. Bukovac and Wittwer (1957) classified a number of nutrients according to their relative degree of translocation in beans after foliar absorption. They found that minerals such as phosphorus, potassium and sodium were mobile and calcium was immobile. These classifications correspond to both the phloem mobility of these elements and the readiness with which they are retranslocated.Other ions such as copper and zinc were found to be 'intermediate' in their ability to move out of the leaf; again this corresponds with what is known about the redistribution of these elements. However magnesium did not follow this pattern as it was deemed immobile by Bukovac and Wittwer (1960). In contrast, Mengel and Kirkby (1978) stated that magnesium moves readily in the phloem and seems to move readily to younger leaves, storage organs and fruit.

This seeming anomaly may be due to the effects of nutrient status of the leaf tissue and general physiology of the plant on nutrient movement.

In the case of foliar-applied minerals, time lapse between uptake and translocation may occur where metabolism of inorganic forms occurs. This has been observed for phosphate (Barrier and Loomis, 1957) although since phosphate is translocated in the phloem, this may not occur in all cases. Nitrogen however would be expected to be subject to such delays as it is transported in the phloem in organic forms only.

2.4 Factors affecting uptake and translocation

2.4.1 Environmental factors

The environments in which roots and leaves function are markedly different in many respects. While temperature will directly affect uptake by both organs, other factors are only applicable to one or the other. Thus light is mainly relevant in the context of foliar uptake, while air supply is applicable only to root uptake. Chemical environment of roots will be dealt with in a later section.

2.4.1.1 Light

Light has an indirect effect on the metabolic aspects of both foliar and root uptake and on subsequent translocation. This is due to the dependency of the metabolic processes on energy derived from photosynthesis. Thus tissues with a low sugar status accumulate solutes less rapidly than tissues with a higher sugar content (Kramer, 1949).

While movement in the xylem may not require energy, loading of solutes into it may (Luttge and Higinbotham, 1976). Phloem transport is highly energy dependent. In addition processes such as nitrate reduction and assimilation require energy.

In the case of foliar uptake, direct effects are also found. Light influences the development of the cuticle (Hull et al., 1975; Reed and Tukey, 1982a, 1982b) and hence subsequent permeability to solutes.

In addition to the indirect effects of light on nitrate reduction mentioned above, there is also evidence that nitrate reduction in leaves is directly stimulated by light (Pate, 1980).

2.4.1.2 Temperature

Temperature has similar effects on root and foliar uptake although it should be noted in the case of the direct affects, that air and soil temperatures are likely to be quite different in any one situation, and so will influence uptake accordingly. In general, uptake increases with temperature within the physiological range in both tissues (Shaw, 1952; Barrier and Loomis, 1957; Middleton and Sanderson, 1965; Nye and Tinker, 1977; Price, 1982). This is probably mainly due to effects on metabolic rates and energy levels. At high temperatures uptake decreases due to damage to enzymes and membranes (Treshow, 1970). Low temperatures may also affect membrane permeability (Nye and Tinker, 1977). Temperature will also influence translocation via its affect on energy (phloem transport) and transpiration (xylem transport).

Foliar uptake will also be influenced by the effects of temperature on the drying rate of the solution on the leaf surface. High temperatures increase the drying rate and hence may reduce uptake.

2.4.1.3 Moisture

Moisture levels affect both root and foliar uptake, however the moisture conditions surrounding the two tissues under favourable conditions are quantitatively so different that the cases are in many ways not comparable. Soil moisture influences both the internal water status of the root and the supply and composition of the soil solution. Thus low internal water status reduces the uptake ability of the root (Nye and Tinker, 1977). At low soil water levels, contact between root and solution is reduced.In addition composition of the solution changes in a complex manner with changes in soil water content. The alteration in boron availability with soil moisture is a good example of this type of effect (Lucas and Knezek, 1972).

The environment surrounding the leaf contains much smaller amounts of water. The relative humidity of the air is only one factor that determines the internal water status of the leaf; soil moisture and other factors such as temperature are also important. Of more importance in determining uptake of foliar-applied nutrients is the effect of humidity on the drying of the solution. At high humidities drying is slower, the uptake period longer and generally greater uptake results (Mederski and Hoff, 1958; Bukovac and Wittwer, 1960). This is to some extent complicated by concentration (Middleton and Sanderson, 1965). As a droplet dries it becomes more concentrated and the diffusion gradient is steeper, favouring uptake. Higher concentrations may also result in damage to the leaf tissue, and slow drying allows time for adjustment of leaf tissue to such osmotic stress.

In addition to solution drying effects, it has been suggested that hydration of the cuticle is important (Shonherr, 1976). If this is so, it may contribute to the favourable effect of high humidities about the leaf.

2.4.1.4 Oxygen

Direct shortage of oxygen around the leaf is not generally an issue although a shortage in the root zone may indirectly influence the physiology of foliar uptake. The uptake of ions by roots is dependent, either directly or indirectly, on metabolic processes for which oxygen is required. Thus lack of oxygen results in a decrease in nutrient uptake (Shaw, 1952; Russell, 1973; Nye and Tinker, 1977). If low levels are maintained for an extended period, tissue damage can occur, resulting in loss of nutrients (Nye and Tinker, 1977). In addition, low oxygen levels lead to reducing conditions in the soil and reduction of Mn (IV) to Mn (II). This results in increased levels of Mn(II) in solution which may give rise to toxicity problems (Murphy and Walsh, 1972).

2.4.2 Solution Factors.

2.4.2.1 Composition

Some ions are more readily taken up by roots than others, for example, nitrate and potassium absorption is fairly rapid while calcium and sulphate uptake is comparatively slow (Mengel and Kirkby, 1978). However, this does vary with other factors such as concentrations of other ions in solution. Williams, (1948) found that supplying additional phosphate enhanced growth, leading to increased nitrate uptake. Similarly, a lack of any required nutrient will result in a reduction in demand for others. Competition between ions also results in variation in uptake for example, magnesium uptake may be reduced by high ammonium or potassium levels in the soil (Mengel and Kirkby, 1978). Certain ions may render others unavailable for uptake; thus high phosphate levels can reduce zinc availability (Lindsay, 1972).

The concentration of H^+ ions in the solution (ie pH) can have considerable effects. These will be dealt with separately.

Foliar uptake can also vary with solution composition, but since the limiting point in uptake is, in most cases, likely to be the leaf surface rather than cell membranes, the ways in which uptake is affected are somewhat different. In addition, with the application of sprays the composition is more controlled than is the case with roots and thus antagonistic effects such as those found between zinc and phosphate can be minimised or avoided.

The form in which the ion is applied also may be important. Orthophosphate seems to be the most readily taken up form of phosphate, although others (for example, tri- and tetra-polyphosphates) may be applied in greater quantities without damage (Barel and Black, 1979).

2.4.2.2 Concentration

Root uptake increases with concentration up to the point at which saturation of the uptake mechanisms occurs (Moore, 1972). A considerable amount of attention has focussed on the details of the relationship; the work has been summarised elsewhere (Luttge and Higinbotham, 1976), and will not be discussed here. At very high concentrations, uptake will decrease due to toxicity and salt (osmotic) effects.

Uptake by leaves increases with concentration up to the point at which tissue damage occurs (Koontz and Biddulph, 1957; Middleton and Sanderson, 1965). Osmotic damage occurs at much lower rates of fertilizer application than would occur with soil application. This is because there is no buffering of concentration as is obtained with soil applications.

2.4.2.3 pH

pH may alter availability of a nutrient in the soil to a considerable degree. For example at high pH, availability of zinc may be much reduced, while at low pH available manganese and aluminium may reach toxic levels. Uptake itself can occur over a wide range of pH (5 to 10 for cations) provided these indirect effects are not limiting (Moore, 1974) but the rate of uptake does vary with pH. Uptake of cations is higher in the neutral part of the range (Arnon et al., 1942; Mengel and Kirkby, 1978).

The pH of foliar-applied solutions can be adjusted to avoid the availability problems that may be present in the soil and thus it is the effect of pH on the permeability characteristics of the leaf surface that is of importance here. Low pH seems to increase phosphate uptake by leaves (Wittwer and Teubner, 1959; Bouma, 1969) but this may depend on the cation in the solution (Koontz and Biddulph, 1957). Uptake of sulphate seems to have little dependence on pH while that of urea shows several maxima and minima over the range pH 2 to pH 9 (Wittwer and Teubner, 1959; Okuda et al., 1960).

2.4.2.4 Other solution factors

Foliar-applied solutions may include other constituents with various functions. The most common of these are surfactants, the purpose of which is to increase retention and solution contact with the tissue. This is done by reducing the surface tension of the solution and hence the contact angle between the solution and leaf surface.

The effect of surfactants varies, possibly due to interactions with other factors. Increased spreading of the droplet may result in increased drying rates, offsetting the effect of increased contact area (Koontz and Biddulph, 1957). The utility of surfactants seems to depend largely on droplet size, large droplets being more effective than a fine spray (Wittwer and Teubner, 1959). Leaf surface characteristics are also important, surfactants being more effective on glaucous (waxy) than non-glaucous leaves (Cantliffe and Wilcox, 1972).

2.4.3 Plant factors

2.4.3.1 Age and position of absorbing tissue.

Absorption varies to some extent with root age, depending on the mechanism of uptake of the ion. Calcium uptake seems to be largely restricted to the apical regions of the root where suberisation of the endodermis is not complete, while potassium and phosphate can be absorbed by root sections several weeks old (Russell, 1977). This may be related to the mainly apoplastic movement of calcium as compared to the symplastic movement of potassium and phosphate to which the suberised endodermis is not a major barrier.

In contrast to roots, leaves may absorb to some extent over the entire life of the leaf and optimum age is independent of the ion. It is generally agreed that young leaves absorb ions more readily than older leaves (Cook and Boynton, 1952; Stewart et al., 1955; Wittwer and Teubner, 1959; Hull et al., 1975). This is probably due to differences in development of the cuticle as in many species the cuticle is thinner and more permeable in younger leaves (Martin and Juniper, 1970). In addition older cuticles are more likely to be damaged than younger ones. In contrast, translocation is greater from older leaves (Koontz and Biddulph, 1957).

In some species, differences in absorption have been observed between upper and lower surfaces of the leaf (Cook and Boynton, 1952; Oliver; 1952; Thorne, 1958) but this is not always the case (Rodney, 1952; Wallihan and Heymann-Herschberg, 1956) and probably depends on relative cuticle development in each case.

Different types of leaf on the same plant may have differing uptake characteristics, as is the case with Phaseolus vulgaris where the primary leaves differ in uptake characteristics to the trifoliate leaves (Hull et al., 1975).

2.4.3.2 Nutrient status of the plant

The rate of root uptake varies depending on metabolic demand (Russell, 1977) and so a mild deficiency of a nutrient is likely to increase root uptake. Severe deficiencies however, will probably interfere with uptake and transport processes and so may result in a decrease in the plants' ability to absorb nutrients.

Foliar uptake, at least of phosphate, does not seem to be affected by the phosphorus status of the plant (Koontz and Biddulph, 1957; Thorne, 1958). Translocation of the foliar absorbed phosphate did vary with phosphorus status however. Under conditions of low supply to the roots translocation was increased (Thorne, 1958), while if no phosphate was supplied to the roots, translocation was reduced. This may be due to problems with phloem function for which ATP is required.

2.4.3.3 Plant species

Both root and foliar uptake vary with species but the basis for the variation may be different in different cases. Root uptake may vary with root distribution and the ability of the plant to change rhizosphere chemistry or absorb ions from very low solution concentrations (or exclude very high levels). Extensive proliferation of roots in the soil may result in increased absorption. A classic example of alterations in the rhizosphere is the case of iron efficient plants such as sunflower (<u>Helianthus anuus</u> L.) which are capable of causing lower pH and more reducing conditions around the root than is found in the bulk soil. These changes result in increased iron solubility, thus increasing the supply to the plant (Romheld and Marschner, 1979).

For foliar applications, variation between species arise from differences in interception and retention of spray, as well as in ease of movement of solutes into the leaf. Characteristics of the cuticle are therefore important in this respect. Baker and Hunt (1981) studied epicuticular wax in a number of species and found a correlation between wax properties and uptake of naphthaleneacetic acid (NAA).

Pineapple (Ananas comosus L.) readily absorbs applied nutrients as do citrus and some varieties of apple (Wittwer and Teubner, 1959). Other varieties of apple do not absorb ions as readily and most species of Prunus take up little if any nutrients from foliar sprays (Wittwer and Teubner, 1959).

2.5 Interactions

There are three ways in which application of a fertilizer may change the uptake of that or other ions by the roots. It may alter the availability in the soil of other ions, the uptake characteristics of the roots , or the growth rate of roots. Soil applications may affect any or all of these three, but foliar fertilizers can influence root uptake only by the latter two methods.

Several studies have found that total uptake by roots can be altered by application of foliar sprays (Thorne, 1955; 1958; Barat and Das, 1962; Alston, 1979), However in none of these cases was a distinction made between changes in root growth and uptake per unit length.

In addition, the interactions found in these studies are unlikely to be simple. Thorne (1955, 1958), working with swedes and sugar-beet found that nitrogen sprays increased root uptake of phosphate and potassium as well as nitrogen. In contrast, Barat and Das (1962) reported a decrease in phosphate uptake by maize roots following application of nitrogen sprays. The physiological conditions affecting these responses requires more study.

Foliar sprays may also affect other aspects of plant function apart from root uptake. Changes in chlorophyll levels following foliar sprays have been observed (Boote et al., 1978; Sherchand and Paulsen, 1985), although the extent of the effect is probably small.

There is also evidence to suggest that phosphate sprays may aid in protection against high temperature injury and salt stress. More work is needed to determine the possible implications of this in production situations.

2.6 Crop responses to fertilizers applied to soil and foliage

2.6.1 Fertilizers applied to the soil.

A vast amount of work has been done on the responses of crops to soil-applied fertilizers. Only general principles will be discussed here.

A generalised pattern of response to increasing amounts of applied fertilizer is shown in figure 2-2 . The curve has three regions showing different responses. The first is the region over which a positive response to fertilizer application is obtained. As may be seen, the response obtained to each increment of fertilizer decreases with the amount applied.

The second region is the range over which no response is obtained to further applications. Thus the quantities already applied are sufficient to supply crop requirements and soil levels of the nutrient are optimum for that crop. The third region is that range in which toxicity occurs and a negative response is obtained to further fertilizer addition.

All the factors discussed above (section 2.3) will influence the shape of this curve (i.e. the slope and the range of fertilizer application over which each region extends). A soil with a high phosphate retention results in a high proportion of applied fertilizer undergoing adsorption reactions thus being less available to the plant. This would result in an increase in the range of each region; i.e. more fertilizer being needed to be added to reach the point where no

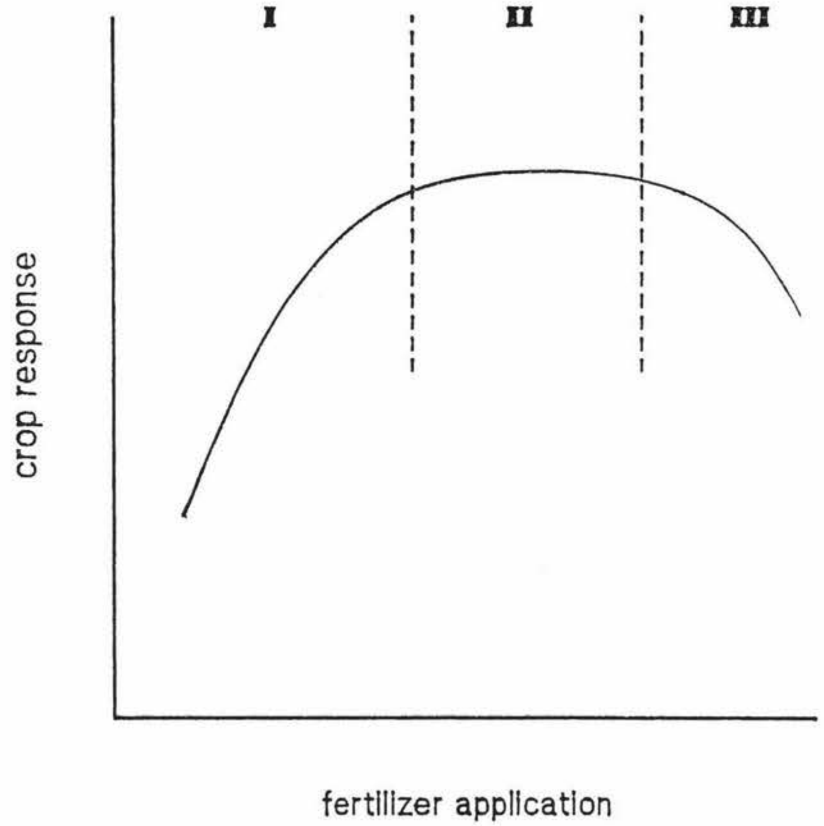

Figure 2-2 Generalised crop response curve for fertilizer application showing ranges of positive response (**I**), no response (**II**) and negative response (**III**).

further response is obtained, as compared to a soil with a lower phosphate retention.

The pH of the soil can also determine the proportion of an applied fertilizer that becomes available to the plant. A high pH reduces the availability of zinc, thus more zinc would need to be applied to reach the point at which no response is obtained.

While there is no doubt that responses to soil-applied fertilizers can be obtained in many situations, it is important to ensure that there is a plant requirement for more of the nutrient than is already available, and that soil and plant factors are such that the plant is capable of utilising the applied nutrient.

2.6.2 Fertilizers applied to the Foliage.

As with applications to the soil, responses to foliar feeding depend on plant requirements, uptake ability and availability of the nutrient. However, there are no soil factors to modify availability in this case and so supply to the plant is more controlled within the quantitative limits set by the method (see 2.1.2.1.). Thus the characteristics of the plant itself and the direct effects of external factors on the plants are more emphasised in this case. A major factor to be considered when looking at foliar feeding is the time period over which responses occur. Due to the nature of the supply process, uptake can occur only over a limited time period. Thus the response will not be continuous as may be the case with soil application. However since supply is directly to the surface, responses can occur very quickly (Wittwer et al., 1963). Thus the technique is particularly useful as an emergency measure.

The following discussion will deal with the literature on the basis of the type of response that has been measured, ie nutrient levels, vegetative growth and yield.

2.6.2.1 Nutrient levels and visual deficiency symptoms.

A certain amount of work has been done investigating the ability of foliar sprays to increase leaf nutrient levels. Unfortunately, there are difficulties in distinguishing between adsorbed and absorbed nutrients. Various leaf washing techniques are used - including spraying with water (Barat and Das, 1962), and washing in 0.1 N HCl (Lauer, 1982). However it is not clear how much adsorbed nutrient this removes or to what degree leaching may occur. This difficulty needs to be borne in mind when discussing effects on leaf nutrient levels.

Foliar application of urea has been observed to increase N levels in plants (Thorne, 1955; Barat and Das, 1962; Magalhaes and Wilcox, 1983). Such responses do not seem to be greater than those obtainable from soil application. Urea is readily taken up by leaves and so may be of use in emergency alleviation of deficiency, but only in conjunction with soil applications as the latter is more likely to be able to supply the plants' full requirements.

Unlike macronutrients, micronutrients can be applied in much more significant quantities as the plant requirement for these elements is so low. Foliar application of zinc has proved to be successful in eliminating deficiency symptoms on a number of crops including soybeans, Phaseolus beans, corn, lima beans and others (Viets et al., 1954; Lindsay, 1972; Banks, 1982; Lauer, 1982). However, difficulties have been noted in correcting zinc deficiencies on tomatoes and potatoes (Murphy and Walsh, 1972). Orphanos (1982) found that although zinc sprays were taken up in apples they did not seem to be translocated and so deficiency was alleviated only in those leaves present at spraying. However, as pointed out in section 2.2, translocation out of the leaf may occur only after the leaf requirements are satisfied, and so continued supply may have been more effective. Wallihan and Heymann-Herschberg (1956) indicated that there may be difficulties in alleviating zinc deficiency by soil application in some situations, especially those favourable to zinc deficiency such as calcareous soils or soil of high phosphate status.

Iron is often applied as foliar sprays as there are considerable problems in correcting deficiencies with soil applications. This is due to the interactions between iron and soils (Mortvedt and Cunningham, 1971; Murphy and Walsh, 1972). Iron availability is decreased at high pH and also at low pH due to antagonism with copper (Olsen, 1972) which becomes more available at these pH's. Inorganic soil applications are generally ineffective unless at very high rates. Chelates may be effective but are expensive and so foliar sprays are generally more economic (Murphy and Walsh, 1972).

2.6.2.2 Vegetative Growth

The use of urea sprays in either spring or autumn to increase shoot growth in apple trees early in the growing season has received a certain amount of attention, with variable results. While sprays often increase spring shoot growth (Fisher et al., 1948; Fisher and Cook, 1950; Shim et al., 1972), comparisons between soil and foliar applications were often conflicting. Shim et al. (1972) obtained a greater increase in shoot growth with autumn sprays than with spring soil application. This could be due to autumn spray increasing nitrogen reserves which may be mobilised before root uptake in spring. Fisher et al (1948) concluded that soil application of urea in spring was more effective in promoting shoot growth than were foliar sprays, also applied in the spring. In contrast Fisher and Cook (1950) concluded that soil and foliar applications were equally effective in increasing shoot growth. Unfortunately no climatic data are given in these papers and so the possibility of differences in soil and air temperatures and the leaching of nitrogen, influencing responses to give these conflicting results in different years cannot be assessed. Leaf area figures at time of spray applications could also be relevant when comparing these results. It is clear however, that while urea sprays may in some cases have a favourable effect on initial shoot growth, they should only be considered a supplementary source of plant nutrient requirements, in conjunction with normal soil applications.

Dry weight increases in response to phosphate sprays have been observed (Silberstein and Wittwer, 1951; Thorne, 1955; Bouma, 1969). In all these cases response to root supply was much more marked. It should be noted however that in two of these studies plants were grown in inert media with nutrient solution and the phosphate concentrations were higher than would normally be in the soil solution. For example, Bouma (1969) used a solution concentration of 3 $\mu g\ g^{-1}$, compared to 0.01 - 0.5 $\mu g\ g^{-1}$ which would be present in the solution of many soils (During, 1984). Comparison of foliar and soil application of K^+ seems to indicate that soil application is preferable (Thorne , 1955). This is not surprising as there are seldom problems with soil application of potassium fertilizers.

The effect of micronutrients on actual growth has received less attention than macronutrient effects. Yogaratnam and Greenham (1982) found no effect of foliar zinc or boron sprays on trunk girth in apples, however no deficiency symptoms were observed. It would be expected that correction of a deficiency by foliar sprays could increase girth where the deficiency is retarding growth.

2.6.2.3 Yield: Quantity

The quantitative yield is the aspect of major interest in most crops. In the pasture situation, vegetative growth is the yield, but in most other situations a particular part of the plant is harvested, the fruit being the most common example. Thus the major economic interest in fertilizer response is response in terms of this harvested yield.

Nitrogen sprays have been shown in a number of cases to increase fruit set in apples (Fisher et al., 1948; Fisher and Cook, 1950; Ford et al., 1965; Shim et al., 1972; Yogaratnam and Greenham, 1982). This may or may not be accompanied by an increase in actual yield. Oland (1963) obtained 50% higher fruit set and yield with a postharvest foliar spray than with soil application. This is in agreement with other studies where increases in yield were obtained (Fisher et al., 1948; Fisher and Cook, 1950; Shim et al., 1972). However Ford et al. (1965) obtained no increase in yield following an increase in set. This may have been due to the low magnesium status of the trees. It is probable that yield increase will result from increased set only if nutritional and other factors are adequate throughout the season to maintain development of the increased number of fruit.

Comparing yield increase from foliar sprays of nitrogen to apples, with those obtained from soil treatment has also resulted in conflicting results. Fisher and Cook (1950) obtained increases greater than those obtained by soil applications while Fisher et al. (1948) found soil application to be more effective. Shim et al. (1972) showed similar increases in yield with autumn foliar and spring soil applications even though increases in fruit set were greater with the foliar spray. Again the necessity for adequate nutrition throughout the season to maintain the advantage of increased set may partially explain these results. In addition, differences in climatic and soil factors affecting uptake (both root and foliar) need to be considered.

Similar effects have been found on other fruit crops. Shawa (1982a) obtained an increase in set and yield with nitrogen sprays on cranberry and suggested that this was related to effects of nitrogen on pollen germination and pollen tube growth. Effects of urea sprays on other fruit crops have proved inconclusive but results may be dependent on other unreported factors making it difficult to assess possible reasons for conflicting results. One possible explanation for the lack of response observed on certain stone fruits (Swietlik and Faust, 1985) may well be the comparative inability of most Prunus species to take up nutrients from foliar sprays (Wittwer and Teubner, 1959).

Yield responses to phosphate sprays have been observed but generally seem to be less overall than those obtainable with soil application. Silberstein and Wittwer (1951) obtained greater total yields in tomatoes with soil application of phosphate than were obtained with foliar sprays, however the yields in the early part of the cropping period were greater with foliar applications. Since a crop such as tomatoes may command a premium price early in the season, foliar applications may well be economically feasible if used in conjunction with the normal soil applications. A similar suggestion was made by Prasad and Brereton (1970) who observed that foliar sprays induced early flowering in potatoes and suggested that phosphate sprays could be used to shorten the growing season for the early potato crop. The possibility of such a use for supplementary sprays warrants more study.

Combination sprays have received considerable attention since Garcia and Hanway (1976) obtained significant increases in soybean

(Glycine max L.) yields with NPKS sprays during seed-filling. Subsequent work on soybeans and other species have yielded varying results, some workers obtaining yield increases (Ozanne and Petch, 1978; Tayo, 1981; Ashour and Thalooth, 1983), and some obtaining no advantage or decreases in yield (Parker and Boswell, 1980; Witty et al., 1980; Poole et al., 1983).

Vasilas et al. (1980) looked at foliar application of NPKS fertilizers to two varieties of soybean in different years. A yield response was obtained in one year but not in the other. Since both varieties were not tested in the same year, it is not possible to assess whether this was a varietal or seasonal effect. The work of Ozanne and Petch (1978) has indicated the differences that may arise between species and Tayo (1981) obtained differing responses with three varieties of cowpea (Vigna **unguiculata** L). Alternatively, the result obtained by Vasilas and his coworkers could have been due to seasonal differences, in particular water relations. In the 1976 experiment (no response) the irrigation techniques were found to be 'inadequate'. Correction of this problem in 1977 corresponded with the improved response. Response to foliar fertilizers does seem to be modified by water stress (Alston, 1979) and it is interesting to note that a number of the adverse responses have been obtained where water stress has been present (Welch, 1977; Witty et al., 1980; Poole et al., 1983).

It has been assumed by Garcia and Hanway (1976) that uptake by the root system decreases or stops during the seed-filling period, due to a decrease in the carbohydrate levels being transported to the root at this time. However Vasilas et al. (1980) found that uptake occurred throughout pod-fill. Possibly the activity of the roots over this stage of development varies with situation, but it should be noted that in none of the above studies was a comparison made with soil applications of fertilizer. Hence the possibility of adequate levels of nutrients such that further additions are not required was not considered. The possibility of spray runoff and subsequent root uptake also needs to be considered.

In summary, responses to foliar applications of combination fertilizers have sometimes been obtained but more work is required to elucidate the conditions under which such responses occur and to what degree, if any, they offer economic advantage over soil application.

Micronutrients offer greater scope for foliar fertilization than do macronutrients due to the small quantities in which these elements are required. Thus a much greater proportion of the plants requirements can be applied in a single spray. For the technique to be effective, however, the nutrient must be reasonably mobile in the plant or regular sprays must be applied to supply new growth.

Boron is one of the more immobile nutrients in plants (Tiffin, 1972) and therefore may not be readily transported to the fruit from leaves after uptake. In annual crops, boron sprays may be used to alleviate deficiencies (Murphy and Walsh, 1972) but this is only a temporary measure in conjunction with soil application. In fruit tree nutrition however, increases in yield have been observed with boron sprays during blossom, even in trees that show no deficiency symptoms and have high leaf boron levels at harvest (Batjer and Thompson, 1949). This was attributed to possible low uptake of boron during bloom and thus low supply to the flowers. Boron is important in the germination and growth of pollen in fruit trees (Swietlik and Faust, 1985), and hence low boron in the flowers could reduce fruit set, however yield increases to boron are not always obtained (Yogaratnam and Greenham, 1982; Swietlik and Faust, 1985) and care needs to be taken as too high a level of boron can be detrimental to fruit quality (see below).

Foliar applications have a particular advantage in the correction of iron deficiencies. Soil applications are often not satisfactory due to interactions with the soil and a number of workers have found foliar fertilizers to be a preferable means of application (Murphy and Walsh, 1972).

The efficacy of foliar application of other micronutrients depends on circumstances. Copper deficiencies have been successfully treated with soil application in most situations, however Grundon (1980) found that soil applications were ineffective in wheat when the crop was water stressed over the growing season. Spraying at mid-tillering and booting stages of growth (to supply vegetative growth and ensure viable pollen production respectively) was found to correct the problem. The effect of irrigation at these stages was not studied.

2.6.2.4 Yield: Quality

Much of the work on fertilizers has focussed on the quantity of harvestable yield produced, but the quality of the produce can be of great importance also. Quality aspects that are commonly of interest are appearance, taste, storage quality and suitability for various types of processing.

One of the best known examples of the effect of mineral nutrition on quality concerns the storage quality of apples, in particular as affected by calcium levels in the fruit. There are several disorders that develop in apples during storage for extended periods including bitter pit and low temperature breakdown (LTB). These disorders have been shown to be related principally to calcium levels in the fruit although K/Ca and Mg/Ca ratios and P levels may also affect one or both of these conditions (Johnson, 1980; Sharples, 1980; Terblanche et al., 1980).

Raising the calcium levels in the fruit by foliar sprays has been shown to be effective in controlling bitter pit development (Schumacher et al., 1980; Van der Boon, 1980). Soil application of calcium has a small effect on calcium levels in the fruit but sprays were necessary to adequately control the development of bitter pit (Van der Boon, 1980).

Phosphate sprays have been investigated in connection with reducing incidence of LTB. This disorder seems to correlate with calcium and phosphate levels early in fruitlet development rather than at harvest

(Sharples, 1980). Yogaratnam and Sharples (1982) found that early phosphate sprays were more effective at controlling LTB than were later sprays and attributed this effect to an increase in phosphate and calcium requirements during the period of active cell division early in fruit development. They suggested that low levels of these elements at this stage results in membranes that are more susceptible to ageing and breakdown.

Boron also has been shown to have a marked effect on fruit quality within a comparatively narrow concentration range. Boron deficiency results in internal cork formation in fruit and cracking of the fruit surface, thus reducing quality. Boron sprays can reduce this problem to some extent and may also improve fruit calcium levels, thus reducing bitter pit incidence (Bramlage et al., 1980; Shorrocks and Nicholson, 1980).

Shawa (1982b) found that two foliar sprays of N-P (10:12:) + 2% Zn improved the storage and eating quality of cranberries. No comparisons were made with similar soil applications.

Quality as affected by mineral nutrition has received less attention for agricultural field crops than for fruit crops. However, nitrogen and sulphur sprays on wheat have been found to increase the protein content of the grain, thus improving the baking quality of the flour (Ralph, 1982). More work in this area would be beneficial in assessing the relative utility of foliar and soil applications of these elements.

2.6.2.5 Other responses

Work on peanut plants (Arachis hypogaea L.) under salinity stress has indicated that phosphate sprays may increase chlorophyll levels and photosynthesis in both stressed and unstressed plants (Malakondaiah and Rajeswararao, 1980). This is in contrast to results by Swietlik et al. (1982a, 1982b) who found a decrease in photosynthesis up to 24 hours after spraying with a complete nutrient solution. The decrease seemed to correspond to a decrease in stomatal and/or mesophyll conductance. However, the plants had fully recovered by the second day. This initial decrease in photosynthesis and subsequent recovery is supported by other workers (Swietlik and Faust, 1985) . The increase noted by Malakondaiah and Rajeswararao (1980) was ten days after spraying. Boote et al. (1978) also noted a slight increase in photosynthesis six days after spraying soybeans with NPKS solution. These results suggest that foliar sprays cause an initial decrease in photosynthetic rate due to effects on CO^2 conductance, that may be followed by an increase once recovery from the initial response has been effected.

The work of Malakondaiah and Rajeswararao (1979, 1980) suggests that phosphate sprays may have a particular role under conditions of salt stress (although the effect of soil application of phosphate under these conditions was not looked at). The adverse effects of salinity on dry weight, leaf area, yield and calcium and potassium uptake were reduced by the sprays. Sprays of KH_2PO_4 are used on wheat in China to counter the effects of hot dry winds during the growing season (Paulsen, 1985). The physiological basis of this is not clear but may be related to effects on membrane stability and potassium levels in the leaf (Sherchand and Paulsen, 1985). These results indicate that more work on the role of foliar fertilizers in stress situations is warranted.

One of the major problems with foliar fertilizers is that of leaf damage, which occurs at much lower rates of fertilizer application than those at which problems occur with soil applications. Sprays with high salt contents can burn the leaf due to the high osmotic potential in the solution and, in some cases, some localised toxicity. An example of the latter case is the presence in urea solutions of biuret, which is toxic to plants and can cause damage in very small concentrations. A concentration of no more than 0.2 % biuret is acceptable in sprays on citrus (Kiang, 1982).

Other factors can influence the amount of damage caused by sprays. Surfactants may reduce damage due to effects on the spreading of the solution (Neumann and Prinz, 1975). Climatic factors are important. High light can result in direct burning due to the concentration of solar radiation by water droplets. Temperature and humidity influence drying rates and hence the rate at which the concentration of the solution on the leaf surface changes. Hence diffuse light, medium temperatures and high relative humidity will minimise tissue damage, while solution factors to be considered include concentration, surfactants and presence of harmful contaminants.

2.7 Beans (Phaseolus vulgaris) and Foliar Fertilzers.

2.7.1 Botany

Phaseolus vulgaris is an annual legume cultivated for seed or the green pod. It has both climbing and dwarf forms, of which the dwarf form is the most important for crop production.

The first pair of true leaves (primary leaves) are single; all subsequent leaves are trifoliate. Primary leaves differ physiologically from the trifoliate leaves and have differing uptake characteristics (Hull et al. 1975).

The cuticle on the leaf of the dwarf bean is thin and fragments when isolated (Martin and Juniper, 1970). Baker and Hunt (1981) studied the epicuticular waxes development on a number of species and found that it was very sparse on beans compared to other species. This corresponded to a high penetration rate of NAA. There was little change in the wax with leaf age. On young leaves epicuticular wax formed an amorphous film while in older leaves platelet structures developed.

The root system of beans is fibrous and may extend to a depth of up to 1.2 m in the field (Gane et al., 1975).

2.7.2 Nutritional requirements

Being a legume, dwarf beans can form symbiotic relationships with Rhizobium spp. However, the formation of effective symbioses does not occur readily (Gane et al., 1975; Barke, 1978) and application of mineral nitrogen is more effective in supplying the needs of the crop (Mullins and Coffey, 1985). Requirements for phosphate and potassium are medium and low respectively, with decreases in yield having been obtained with potassium application if soil levels are high (Barke, 1978).

Adequate sulphur is required for good yields as too high a N:S ratio favours vegetative growth at the expense of reproductive growth (Lluch et al., 1983).

Beans are very sensitive to both zinc and boron levels. Tissue zinc levels below 20 - 30 $\mu g\ g^{-1}$ result in reduced yields and may delay the time to maturity (Boawn et al., 1969; Barke, 1978). Boron levels are important as beans are sensitive to both deficiency and toxicity of this element (Mesdag and Balkema-Boomstra, 1984) as well as to high levels of manganese.

The sensitivity of beans to levels of these elements makes pH fairly important in bean production as low pH may result in high manganese availability and resulting toxicity problems, while high pH may lead to zinc deficiency, especially if soil phosphate is high (Melton et al., 1970).

2.7.3 Foliar fertilizers and beans.

Beans have been used frequently in studies on the physiological aspects of foliar uptake including studies on the nature of uptake (Jyung and Wittwer, 1964), translocation (Bukovac and Wittwer, 1957; 1960; Karhadkar and Kannan, 1984), and factors affecting uptake (Koontz and Biddulph, 1957; Bukovac and Wittwer, 1960; Okuda et al., 1960). This work has been dealt with in sections 2.1 -2.3 and will not be discussed further here.

In contrast to the amount of work done with beans concerning the physiological aspects of foliar uptake, comparatively little has been done on the effects of foliar sprays in the field. Lauer (1982) obtained no yield response to NPKS and zinc sprays on beans. However in this study, adequate soils levels of all these nutrients were ensured before spray application. Thus there was unlikely to be much requirement for further application whether by soil application or foliar sprays. Weaver et al. (1985) obtained an increase in yield factors with foliar sprays of various compounds known to enhance pollen tube growth, including calcium nitrate and boric acid. The increase was attributed to increased set and pod retention.

Thus the use of foliar sprays on bean crops in the field has not been adequately researched. In view of the ease with which beans absorb foliar-applied nutrients further work on this crop is warranted.

2.8 Conclusions

Responses to foliar applications of fertilizers can sometimes be obtained, but if the technique is to be used effectivly, certain points must be considered. Firstly, the plant must be capable of utilizing the applied nutrients. Some plants absorb nutrients through the foliage more effectively than others, thus foliar application is more likely to be effective on a bean crop than in a stone fruit orchard. It is also necessary to have some basis for expecting a response to the application of the nutrient. (This applies to fertilizer application by any method but is sometimes overlooked in consideration of foliar application.) The presence of low nutrient levels in the plant is the most common basis for expecting a response but may not be the only one.

It is also important to consider the quantities of nutrients that can be applied by foliar sprays, and to what degree that quantity can be expected to result in the required response.

Application of foliar sprays can also affect various aspects of plant function. The net result of these effects may vary considerably and a better understanding in this area would be useful in assessing the utility of foliar sprays as a fertilizer technique.

Finally, application of the spray should be carried out under conditions favouring maximum positive response. This includes consideration of environmental factors as well as timing with respect to crop development and requirements.

When comparing foliar sprays with soil application, it is necessary to consider the factors (environmental,soil and plant) affecting both processes to enable prediction of circumstances in which foliar application may be preferable to soil. The supplementary nature of foliar application in the context of crop fertilization needs to be emphasised more than it has been in the past.

CHAPTER 3

CHAPTER 3

MATERIALS AND METHODS

3 .1 Preparation of plants.

All experiments were carried out in the glasshouse using beans (Phaseolus vulgaris var. Gallatin). Two pot sizes were used. Small pots (700 cm^3) had a base diameter of 9 cm and a depth of 9 cm. Large pots (3 litre) had a base diameter of 13 cm and a depth of 19 cm.

Where plants were grown in soil, (chapters 4, 5, and 7), a Manawatu fine sandy loam was used. Soil was collected from the top 20 cm, air dried and sieved (< 2mm). Manawatu fine sandy loam is a slowly accumulating recent soil from alluvium. Natural nutrient status is good, with high phosphate and calcium and medium potassium levels (Cowie 1978).

To obtain an estimate of a suitable water content for plant growth, a pot of soil was saturated and left, covered, to drain for 36 hours. This resulted in a gravimetric water content of 0.22, which appeared to be satisfactory for good plant growth. The weight of the pots at this water content was used as a basis for addition of distilled water to supply plant requirements.

3.2 Nutrient applications.

Spraying of solutions was done using a hand sprayer capable of dealing with small volumes, ie, less than 15 cm^3. An air compressor supplied the necessary air flow.

Spot applications were used for the isotope experiments. Droplets were applied to the midrib of the appropriate leaf midway along the leaf length (see figure 4-1). A peristaltic pump was used with tubing of 0.25 mm (0.01 in) internal diameter to give a flow rate of 0.05 cm^3 min^{-1}. This gave accurate and consistent measurement of droplet volume and minimised the risk of isotope contamination of other parts of the plant.

3.3 Plant tissue preparation

Plant tops were harvested by cutting at the cotyledons, dividing into parts where these were to be separately analysed, and weighing. Samples were then oven dried at 68 °C for 24 hours. In the case of seedpods, drying for a minimum of 48 hours was necessary due to the size and density of the tissue.

Samples were then ground using a coffee grinder.

3.4 Nutrient analyses

3.4.1 Total Sulphur

Total sulphur was determined using the Leco induction furnace and titrator as described in Jones and Isaac (1972); however quantities of accelerants were reduced due to difficulties with overflowing of samples in the induction furnace, leading to damage of the combustion chamber.

Preparation of reagents was as described in Jones and Isaac (1972). Procedure:

A 0.05 g sample of plant tissue was weighed into a combustion crucible containing 1 small scoop (0.3g) iron accelerator. Two small scoops (totalling 0.2g) of magnesium oxide were placed over this, completely covering the sample. The crucible was then placed in a muffle furnace and heated to 500 °C for 1 hour. After cooling, 1 scoop each of iron and tin accelerators (0.95g and 0.85g respectively) was added. The crucible was covered and placed in the induction furnace. An analysis time of 6 minutes was found to be required to ensure complete combustion. Back titration with potassium iodide-iodate solution was carried out automatically with a Leco titrator.

3.4.2 Total Phosphorus

Phosphorus content was determined by Kjeldahl digestion as described in Twine and Williams (1971). This was followed by a vanadate-molybdate colormetric analysis using an auto-analyser.

Reagents:

Digestion mixture was made by dissolving 100g K_2SO_4 and 1 g of Se powder in 1 litre of concentrated H_2SO_4 by heating to 250 °C for 3 hours.

Molybdate/vanadate solution. A molybdate solution was made by dissolving 62.5 g $(NH_4)_6Mo_7O_{24}.4H_2O$ in approximately 1000 cm^3 water and heatong (not above 55°C). A vanadate solution was made by dissolving 3.125 g NH_4VO_3 in approximately 1000 cm^3 H_2O, heating and then cooling, and adding 67.5 cm^3 concentrated H_2SO_4. The two solutions were then added together and made up to 2.5 litres

Alkali phenol consisted of 200g phenol, 165g NaOH and 285g sodium potassium tartrate, dissolved in H_2O and made up to 2.5 litres

Procedure:

Approximately 0.1g of dried plant tissue was accurately weighed into a digestion tube and 6 cm^3 of the digestion mixture added. This was then digested for three hours at 300°C, cooled and made up to 50 cm^3. The solution was left to settle and then analyzed for phosphate on the autoanalyzer. The flow sequence for the analysis is shown in figure 3-1.

3.4.3 Total Zinc

A dry ashing procedure was used for zinc determinations as outlined by Belesky and Jung (1982).

A 0.2g sample of plant tissue was weighed into silica crucibles and dry ashed in a muffle furnace for 10 hours.

The temperature was raised to 450°C at a rate of 100°C hr^{-1} and then maintained at this temperature for the rest of the required time. The ash was dissolved in 2 cm^3 of 1M HCl and heated for 1 hour, maintaining the solution below boiling point then filtered with acid-washed filter paper and made up to 18 cm^3. Total Zn was determined by atomic absorption spectroscopy.

3.5 Isotope analyses

3.5.1 Sulphur-35

S^{35} activity was measured by liquid scintillation counting following a sodium hypobromite digestion.

Reagents

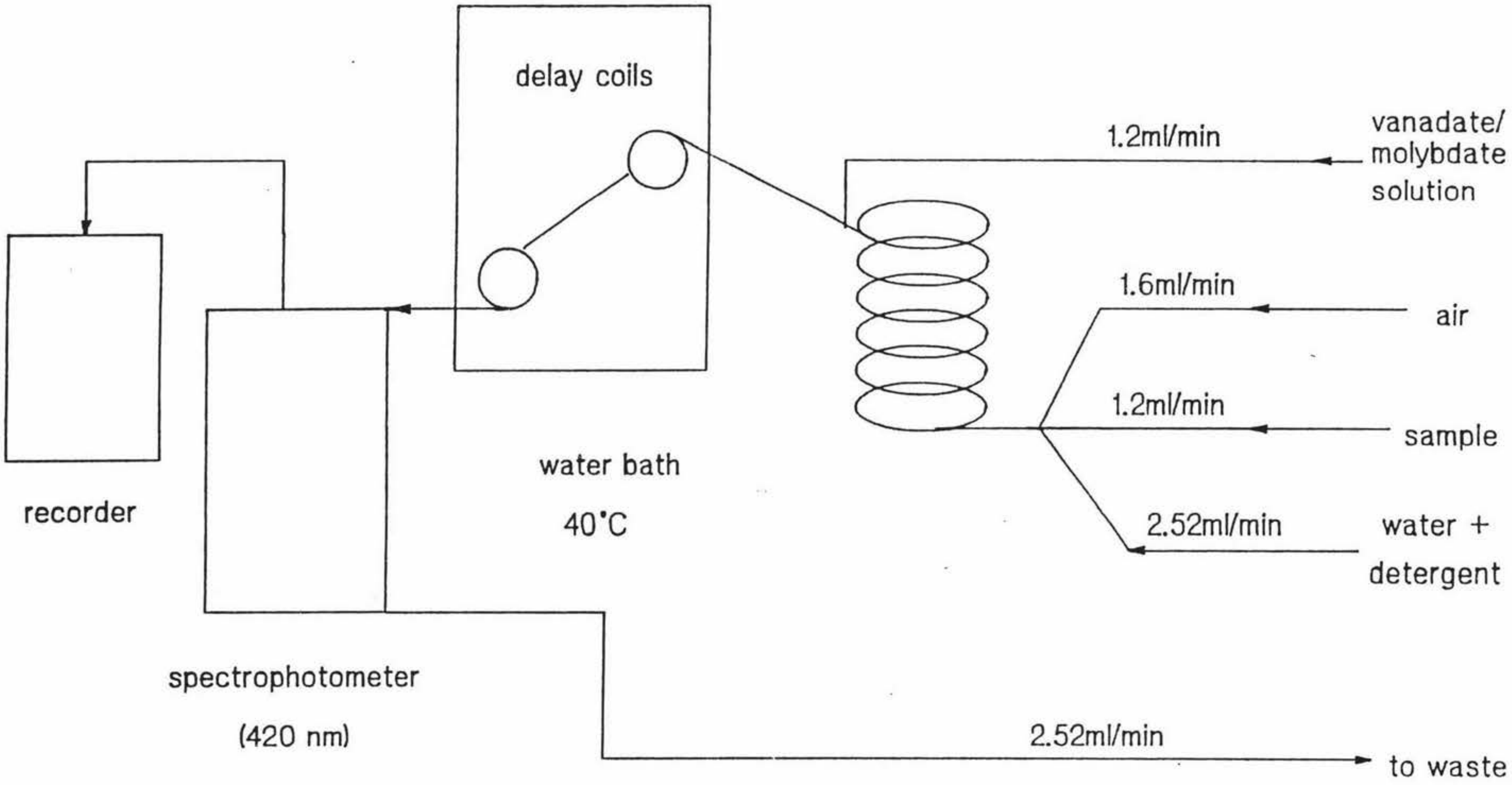

Figure 3-1 Flow sequence for the determination of phosphorus in plant material.

Sodium hypobromite was made by adding 3 cm^3 of bromine to 100 cm^3 of 2M NaOH. This solution was made freshly each day.

Scintillation cocktail consisted of 4g PPO (2,5 diphenyloxazole) and 0.1g POPOP (2,2-p-phenylene-bis (4-methyl-5-phenyl oxazole), dissolved in 670 cm^3 toluene and 330 cm^3 triton-X 100 (Patterson and Greene 1965).

Procedure:

A 0.03g sample of plant tissue was weighed into a digestion tube, 1 cm^3 NaOBr added and the whole digested at 150°C for 30 minutes. Two cm^3 of NaOBr were added and digestion continued at 200°C for 60 minutes. It is important that the sample evaporates to dryness at this stage (Tabatabai and Bremner, 1970). A further 1 cm^3 of NaOBr was added and further digestion at 250°C for 30 minutes carried out. The sample was then cooled, resuspended in 10 cm^3 of deionised water and left for four hours.

Aliquots of 1 cm^3 were taken and placed in plastic scintillation vials. Scintillation cocktail (10 cm^3) was added and the samples read on a Beckman LS 3801 scintillation counter.

Counting efficiencies were determined by constructing a calibration curve relating H# and counting efficiency. A series of vials were prepared containing equal activities of S35. To these were added differing quantities of chloroform. Chloroform was used as a quenching agent due to the very small quantities that are required to obtain appreciable quenching, resulting in negligible sample volume changes. These samples were then read on the scintillation counter, counting efficiencies calculated and plotted against H# (figure 3-2). From this the counting efficiency of each sample could be determined using the H# given with each reading.

3.5.2 Phosphorus-32

The method used involved counting of Cherenkov radiation in the aqueous solution (Brown, 1971). A 15 cm^3 aliquot of the solution obtained following Kjeldahl digestion (section 3.4.2) was placed in a vial and read directly. Counting efficiency was determined by rereading each sample after addition of an internal standard.

3.5.3 Zinc-65

For determination of Zn^{65} activity, a one cm^3 aliquot of the solution obtained from the dry ashing procedure (Section 3.4.3) was placed in a vial. Scintillation cocktail (10 cm^3) was added and the samples read. Counting efficiencies were determined by obtaining a H# calibration curve (figure 3-3) as described for S^{35} analysis (section 3.5.1).

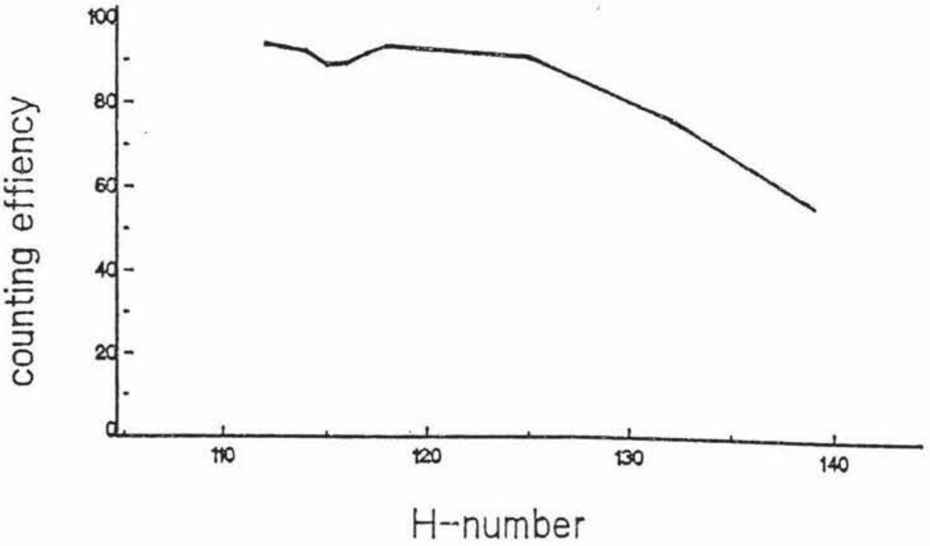

Figure 3-**2** Curve relating H-number and counting efficiency for S^{35}.

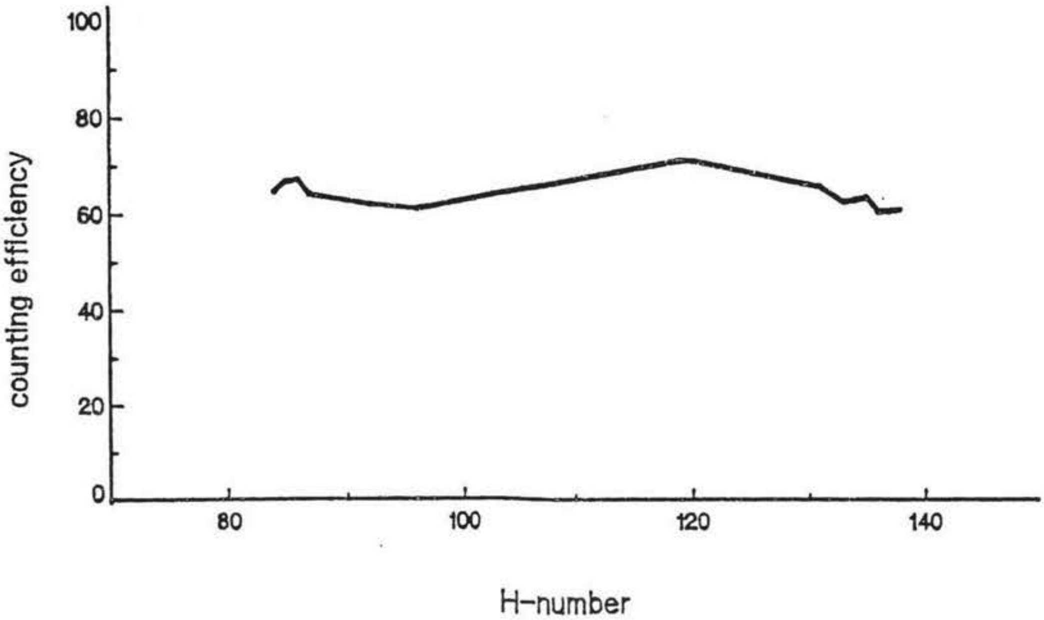

Figure 3-**3** Curve relating H-number and counting efficiency for Zn^{65}.

CHAPTER 4

CHAPTER 4

DISTRIBUTION PATTERNS OF S^{35} IN BEANS PHASEOLUS VULGARIS FOLLOWING ROOT AND FOLIAR UPTAKE.

4.1 Introduction

Although uptake of foliar-applied nutrients is known to occur (Wittwer and Teubner, 1959; Wittwer et al., 1963), it is also important to consider subsequent utilization of the absorbed nutrient when assessing foliar fertilization as a technique.

In most crops there is a particular part (ie the harvestable portion), that is of interest to the grower, for example, the roots for swedes, flowers for cauliflower and seeds for beans. Thus, provided that levels in the leaf are adequate to ensure continued carbohydrate production, it is supply to this part that is of particular importance.

When comparing root and foliar uptake of nutrients, it has been found in a number of cases that foliar uptake is more efficient in terms of recovery of applied fertilizer than is root uptake (Barat and Das, 1962; Datta and Vyas, 1967; Wittwer et al., 1957), at least in the short term. However, as well as total recovery, it is also of interest to look at relative supply to the harvested parts. This has been done in several studies using phosphate, and seems to indicate a possible advantage of foliar application (Prasad and Brereton, 1970; Wittwer et al., 1957).

While some comparative studies have been carried out with sulphur on various plants (Biddulph et al., 1958; Bouma et al., 1972 as quoted in Bouma, 1975; Bukovac and Wittwer, 1960; Levi, 1968), little has been done with plants that have developing fruit.

In this experiment, movement of S^{35} was observed following root and foliar uptake by beans at the mid pod-fill stage of growth, and distribution patterns compared.

4.2 Method

Seeds were germinated and planted out in 31 pots containing approximately 2600g air-dry soil and watered to a gravimetric water content of 0.22. Plants were then grown in the glasshouse for seven weeks at which time treatments were applied.

Each plant received two foliar applications and one soil application of 0.05M K_2SO_4. Soil applications consisted of 2 cm^3 of solution applied to the soil surface around the stem. The two foliar treatments consisted of spot applications (see section 3.2.(i)) to the midrib of the center leaflet of the first and third trifoliate leaves (figure 4.1). Treatments consisted of incorporating S^{35} label in the solution for one of the three applications:

Treatment 1 Application of S^{35} to third leaf
Treatment 2 Application of S^{35} to first leaf
Treatment 3 Application of S^{35} to soil

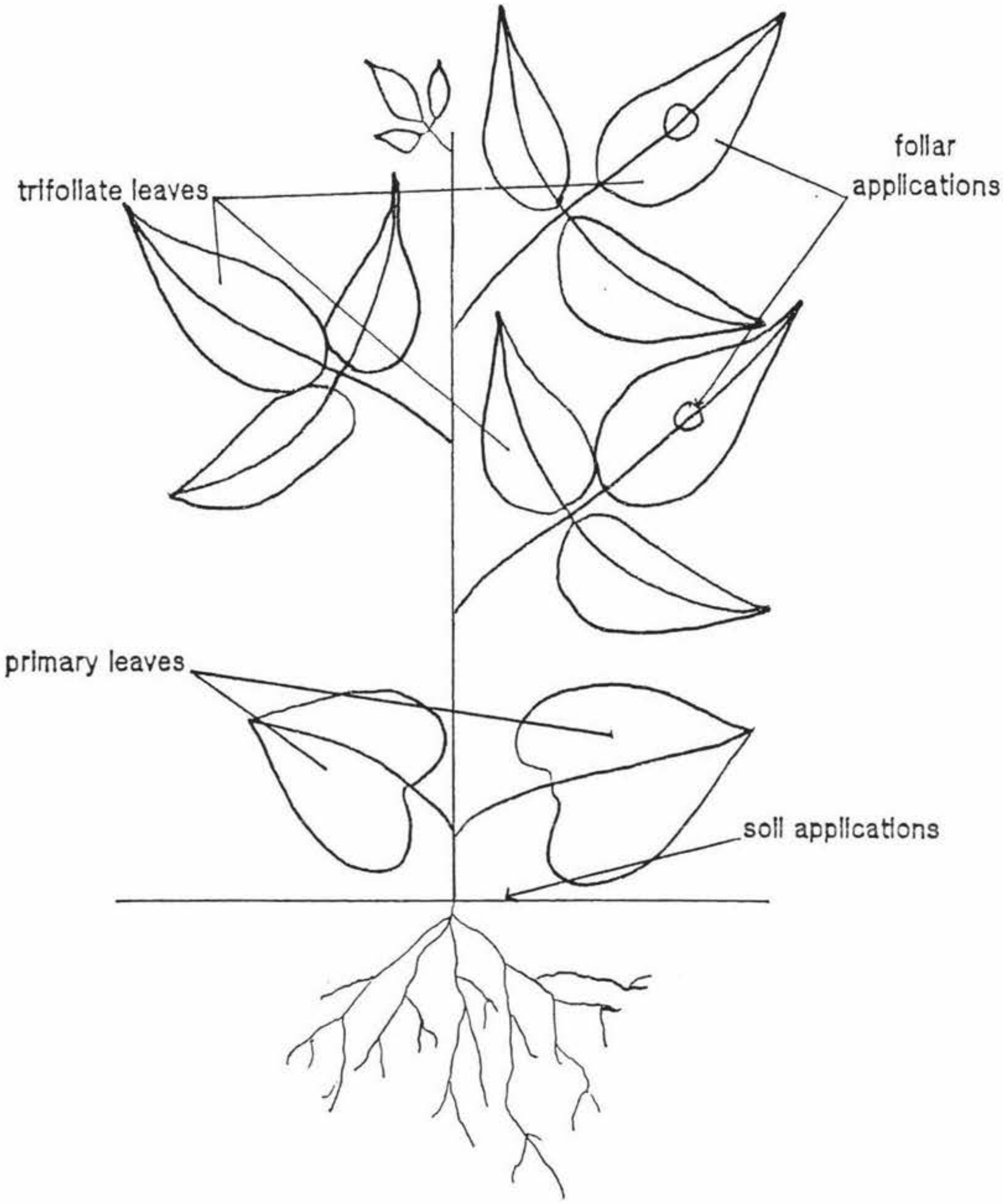

Figure 4-1 Position of application of K_2SO_4 (0.05M) to soil and the first and third trifoliate leaves

Treatments were replicated 5 times.

Plants were left for four days after application, then harvested and divided into roots, stems, fruit, leaves (including the petiole) and the leaf to which the label was applied in the case of foliar applications. Roots were extracted from soil by removing from the pot and exposing the root system by dry excavation (Bohm 1979). Isotope analyses were not done on roots, as contamination by soil would preclude obtaining a figure for actual uptake.

Samples were dried, weighed and ground. Herbage was analysed for total sulphur using the Leco method (section 3.4.1) and for S^{35} activity by liquid scintillation counting (section 3.5.1). Specific activities for each plant part were then calculated.

Two plants were also treated for autoradiography. In this case application was to the soil and the first trifoliate leaf only. Soil application was as for treatment 3. Foliar application consisted of application to the midrib of each of the leaflets of the leaf. Preliminary experiments had shown this to be necessary in order to supply sufficient isotope to show on the autoradiographs. One plant received S^{35} in the soil application, and the other in the foliar application.

Plants were harvested after four days and laid out in an exposure cassette. In the case of the soil application the plant was fitted into one cassette, but for the foliar application it was necessary to divide the plant up. A thin polythene film was placed between the plant tissue and the film to prevent chemical artifacts developing.

The film used was Kodak X Omat TL. The exposure time was different for the two treatments; 3 months for the soil treatment, and 10 months for the foliar treatment. Thus comparisons of densities between autoradiographs are not appropriate. Film was developed using an automatic developer.

4.3 Results

Total sulphur concentrations (table 4-1) were low compared to figures given by Barke (1978) for the youngest mature leaf, ie 4000 µg g^{-1}, indicating that the plants were probably deficient in sulphur. In addition S levels seemed to be fairly uniform throughout the plant.

Results for total recovery of isotope were low. For soil application this would be expected due to adsorption and exchange reactions in the soil. For foliar applications recovery would be expected to be quite high, however in this case, due to the method of application, unabsorbed isotope would be present at a very high concentration on a very small proportion of the leaf, making estimates of actual activity in the leaf to which isotope was applied difficult. This is reflected in high subsampling variation for activity in this tissue.

Total uptake figures varied between plants and treatments. (Table 4-2) It is not possible to compare the uptakes for soil and foliar

[ABLE 4-1 Total Sulphur in plant parts ($\mu g\ g^{-1}$)

[reatment	leaves	fruit	stems	roots
1	2225 (340)	2315 (242)	2589 (354)	2828 (422)
2	2466 (337)	2413 (201)	2406 (233)	2803)394)
3	2244 (506)	2428 (453)	2252 (125)	2522 (324)
mean	2312 (389)	2385 (299)	2427 (278)	2718 (382)

( ) =standard deviation

treatments in this case as the soil-applied S^{35} would have exchanged to some extent with the sulphur in the soil, effectively diluting the activity. There was a trend for activity found in the rest of the plant to be slightly lower with uptake by the upper leaf compared to uptake by the lower, indicating that either uptake or translocation to other parts of the plant was greater following application to the lower leaf. There is general agreement in the literature that younger leaf tissue absorbs solutes more readily than does older tissue (Hull et al., 1975; Stewart et al., 1955; Wittwer and Teubner, 1959) and so it is probable that these results indicate greater translocation from the lower leaf.

Since the level of isotope uptake varied between plants even within treatments, it was difficult to look at distributions using specific activities themselves. Therefore an average specific activity was calculated for each plant and a ratio (a) obtained for each sample (table 4-3)

$$\alpha = \frac{\text{specific activity of plant part}}{\text{average specific activity of plant}}$$

This enables comparisons of distribution patterns independent of uptake.

The α values for leaves showed no differences between soil and foliar application, however there was a trend for application to lower leaves to result in higher isotope concentrations in the leaves than did application to the upper leaf. This trend was not statistically

TABLE 4-2 Recovery of applied S^{35} in plant parts and distribution of S^{35} within the plants

Treatment	plant	total recovery	isotope content in plant parts:				
		(% of applied)	as % of total in tops			total dpm (x10^5	
			leaves	fruit	stems	tops	fruit
1	1	18.5	0	95.7	4.3	8.6	8.2
	2	47.6	5.8	81.6	12.6	5.5	4.4
	3	*	*	*	*	*	*
	4	44.0	2.4	65.2	32.4	2.6	1.7
	5	30.9	1.9	26.6	71.5	14.6	3.1
2	1	75.2	26.3	59.9	13.8	13.7	7.8
	2	95.6	12.3	63.2	24.5	9.0	5.0
	3	45.4	41.1	41.6	17.3	19.0	7.3
	4	67.7	28.7	55.3	16.0	18.5	10.1
	5	54.7	7.9	56.0	36.1	9.7	4.6
3	1	0.02	0	76.4	23.6	12.0	0.9
	2	0.03	18.3	33.4	48.3	68.8	23.0
	3	0.63	30.3	37.2	32.5	102.2	38.0
	4	0.32	11.9	41.6	46.4	63.0	26.2
	5	0.29	20.3	41.4	38.3	44.3	18.4

* missing values

significant, however a similar trend was also evident in the figures for total isotope distribution with the difference in leaf content being significant ($P<0.05$).

The α values for the fruit (Table 4-3) indicated that, for all treatments, the relative concentration in the fruit was higher than in the rest of the plant. There was no difference between treatments.

Stem α values were higher following root uptake compared to foliar uptake. This may have been due to differences in the proportion of the stem that is used as a pathway. For soil uptake, movement occurs throughout the stem, while for foliar uptake, only a part of the stem is involved in initial movement, especially if the bulk of the movement is to subtending fruit as is indicated in figure 4.2a.

Figures 4.2a and 4.2b show the autoradiographs for foliar and soil treatments respectively. Foliar application resulted in movement to the subtending fruit only with no activity observed in any other part of the plant. The autoradiograph for soil application indicated movement throughout the plant although only traces were observed in the primary and first trifoliate leaves.

4.4 Discussion

The figures for total S indicate a uniform distribution pattern throughout these plants. Biddulph et al. (1956) showed the normal distribution of S as a function of S supply in vegetative bean plants.

TABLE 4-3 Ratios (α) of specific activity of plant parts to the average specific activity of the whole plant.

Treatment	leaves	fruit	stems
1	0.07 (0.06)	2.43 (1.31)	0.97 (0.85)
2	0.45 (0.31)	2.57 (0.28)	0.89 (0.38)
3	0.26 (0.21)	2.25 (1.09)	1.80 (0.41)

( ) = standard deviation.

They found that, while roots and trifoliate leaves tended to have higher levels of S than the stems or primary leaves, at very low levels of S supply these differences were much reduced. Thus the uniform distribution observed here may be due in part to the low S status of the plants.

The tendency for leaf α values to be higher following application to the lower leaf than after application to the upper leaf could be a result of leaf age. The rate of protein synthesis decreases with leaf age in mature leaves (Bidwell, 1979) and thus the incorporation of S^{35} into leaf proteins would be less in the lower (older) leaf. This in turn could result in S^{35} being more readily translocated out of the leaf than is the case with the younger leaf. This would also explain the tendency for translocated counts to be higher with application to the lower leaf than to the upper leaf. (table 4-2)

The α values indicate an increased relative movement of isotope to the fruit compared to other plant parts. All treatments had a similar increase. This seems to be in contrast to the results obtained by autoradiography where movement throughout the plant occurred following soil application, while most of the movement following foliar application was to the subtending fruit.

This may be explained by the bulking of all fruit on a plant for analysis. Thus, in the comparisons of α values, no account is taken of possible distribution between fruit at different positions on the plant. The autoradiographs indicate that, even where the proportion of an applied nutrient that moves to the fruit may be the same for differing application methods, the distribution of the applied nutrient may not be the same. The implications of this when applying nutrients on a larger scale (for example application to each leaf rather than just one) are difficult to assess from these results and more work would be required to elucidate this aspect.

Studies on S movement in beans (Biddulph et al., 1956; 1958) indicate that, following root uptake, S moves throughout the plant initially and may then undergo redistribution to some extent to areas of high sink activity. Further circulation however, seems to be limited by incorporation into immobile fractions such as proteins.

Autoradiography, (figure 4-2) indicates that if any major translocation to the primary or first trifoliate leaf did occur following soil uptake, most of this was subsequently retranslocated to younger leaves and fruit leaving only traces in the older tissue. With the liquid scintillation counting, no distinctions were made between mature and immature leaves so it was not possible to assess the relative distribution in leaf tissue of different ages.

Foliar-applied S could be expected to show the same pattern as retranslocated soil absorbed isotope, ie to younger leaves and fruit. As all leaves were bulked regardless of age and the autoradiograph for foliar application did not pick up any movement to the leaves, it is not possible to assess to what degree the activity found in the leaves was present in the younger (immature) leaves. However the main movement in all treatments. seemed to be to the fruit. This is not surprising as the fruit often constitute a strong sink and in many

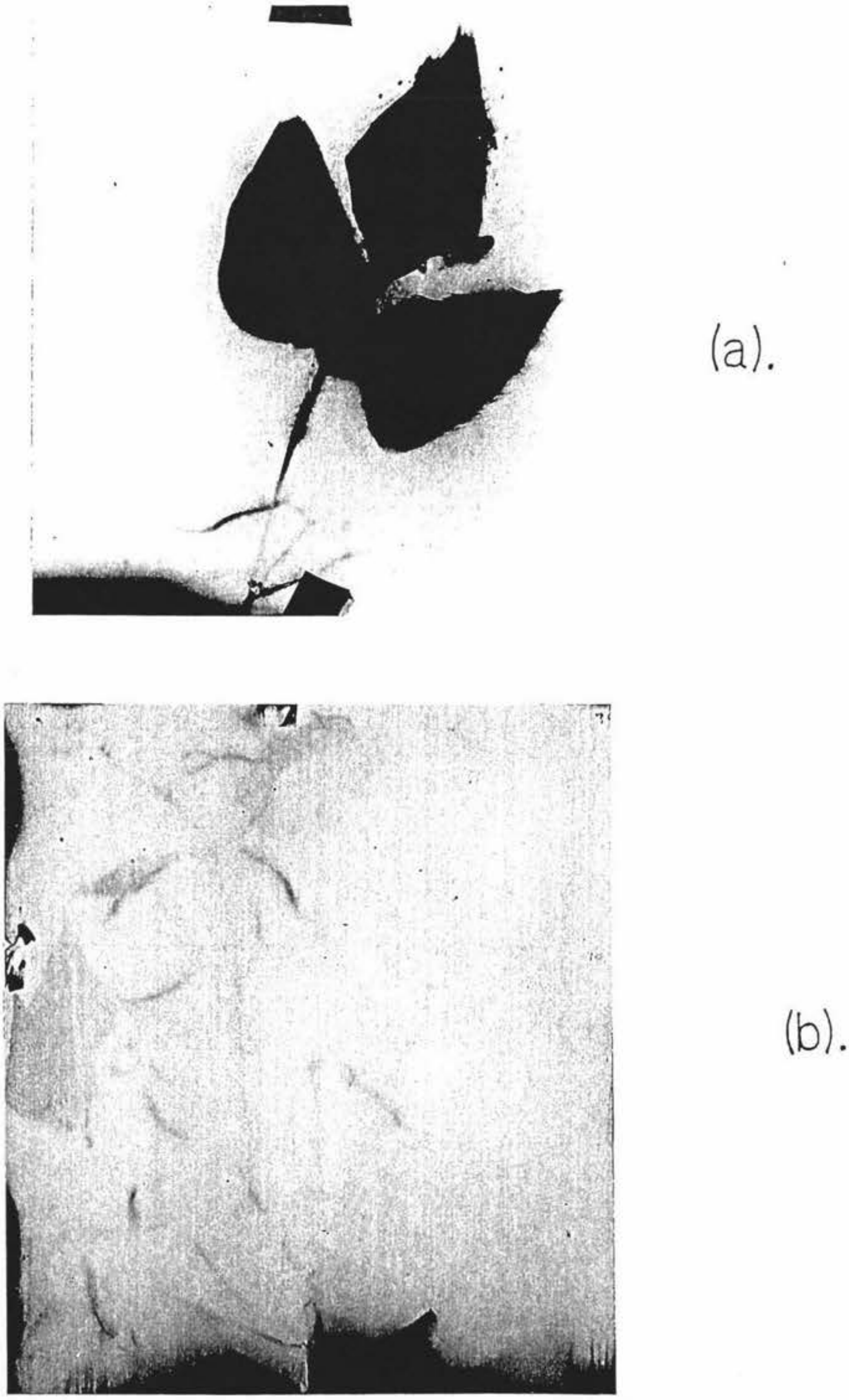

Figure 4-2 Autoradiographs of bean (Phaseolus vulgaris) plants following uptake of S^{35} applied to a leaf (a) and roots (b).

plants vegetative growth is much reduced during fruit development (Bollard, 1970).

These results indicate no advantage of foliar application of S^{35} over soil application in terms of translocation to the fruit. More work is required to assess the effect differences in distribution between fruit may have when nutrient application is carried out on a larger scale.

In addition, a few points do need to be considered. Mobility characteristics of sulphur can vary (Bouma, 1975; Loneragan et al., 1976) depending on the physiological condition of the plant, and so the result found here may not be found in all situations. In addition, similar efficiency of supply to the fruit does not necessarily imply a similar quantitative supply. The amounts of sulphur applied in this experiment are much lower than would be required for yield responses and at higher rates differences in efficiency of supply to fruit may become evident. Also, the limits in quantity that can be applied to the foliage without damage must be considered (chapter 2).

CHAPTER 5

CHAPTER 5

DISTRIBUTION PATTERNS OF P^{32} AND ZN^{65} IN PHASEOLUS VULGARIS FOLLOWING ROOT AND FOLIAR UPTAKE.

5.1 Introduction

Results obtained with sulphur (chapter 4) indicated that there was no advantage of foliar application compared with soil application in terms of supply to the fruit. Such a result is dependent on the nutrients' transport characteristics in the plant and so it is of interest to compare nutrients with differing characteristics.

It has been suggested that of the macronutrients, phosphate is the most likely to benefit from foliar fertilization as it is required in smaller quantities than nitrogen or potassium and is subject to adsorption processes which reduce its availability to plants to a considerable degree in many soils (Silberstein and Wittwer, 1951). Phosphate is quite mobile in the plant, being readily translocated and cycling in the plant to a greater extent than sulphur (Biddulph et al., 1958).

Much of the current commercial use of foliar fertilizers involves application of micronutrients such as zinc. Zinc availability in soils may also be reduced by adsorption processes (Lindsay, 1972) and its mobility in plants is variable (Loneragan et al., 1976). This is reflected in conflicting results obtained for translocation of foliar-applied zinc, with translocation being observed in some cases and not in others (Stewart et al., 1955; Wallihan and Heymann-Herschberg, 1956).

In this experiment, movement of P^{32} and Zn^{65} were observed following root and foliar uptake by beans at the mid pod-fill stage of growth.

5.2 Methods

Plants were grown in 17cm pots for 8 weeks after which time treatments were applied. Each plant received one foliar and a soil application of either 0.01M K_2HPO_4 or 1mM $ZnSO_4$. In each case one of the applications was labelled with the appropriate isotope (P^{32} or Zn^{65}).

Treatment 1: P^{32} added to foliar application
Treatment 2: P^{32} added to soil application
Treatment 3: Zn^{65} added to foliar application
Treatment 4: Zn^{65} added to soil application

Soil applications consisted of application of 2 cm^3 of solution to the soil surface around the stem. Foliar applications consisted of spot applications of 0.06 cm^3 to each of the three leaflets of the second trifoliate leaf. There were 7 replicates per treatment.

Plants were left for 4 days, then harvested and divided into leaves, stems, fruit (including flowers), and in the case of foliar applications, the leaf to which the isotope was applied. Roots were not harvested in the case of the soil-applied isotope, as contamination by the soil would preclude obtaining a figure for actual uptake.

The plant tissue was then dried and weighed. Treatments 1 and 2 were analysed for total P using autoanalysis (section 3.4.2) and P^{32} activity determined by Cherenkov counting (section 3.5.2). Treatments 3 and 4 were analysed for total Zn by atomic absorption (section 3.4.3) and Zn^{65} activity by liquid scintillation counting (3.5.3). Specific activities were obtained and α values calculated as described in chapter 4.

5.3 Results

The total P concentrations (Table 5-1) were low compared to those given by Barke (1978), figures of the order of 2000 $\mu g\ g^{-1}$ being obtained compared to the 4000 $\mu g\ g^{-1}$ quoted by Barke for the youngest mature leaf. This implies that the plants were deficient in this element. There was a significantly higher P concentration in the fruit compared to the rest of the tops ($P<0.01$). Zn concentrations seemed to be adequate, but not high, a figure of 30 $\mu g\ g^{-1}$ being given by Barke (1978) for the minimum in young mature leaves. Lowest Zn levels were found in the fruit ($P<0.01$) and the highest in the stems ($P<0.05$).

The α values (table 5-2) indicate significant differences between elements in isotope movement to the various plant parts, and for both elements these were influenced by the mode of application. Zn^{65} activity following soil uptake showed a similar pattern to that

TABLE 5-1 Total P and Zn ($\mu g\ g^{-1}$) in bean plants (average over treatments)

	leaves	fruit	stems
P	2051 (226)	2721 (268)	1866 (248)
Zn	44.2 (11.9)	30.8 (9.2)	56.7 (15.1)

( ) = standard deviation

observed in total concentration figures with lowest levels in the fruit and highest in the stems ($P<0.01$). In contrast, P^{32} activity did not follow the same pattern as total P, activity being lower in the fruit than the rest of the tops ($P<0.01$). This could arise from differences in the distribution of root absorbed P at different stages of fruit development, or from redistribution from leaves occurring over longer periods than four days. Possibly both of these reasons contribute to the effect.

For both Zn^{65} and P^{32}, foliar application resulted in a much higher relative concentration of isotope in the fruit compared to the soil application. However the difference in distribution of total P and P^{32} mentioned above indicates that the isotope results may not show the final distribution of root absorbed P and that over the whole period of fruit development relative movement of P to the fruit may be greater than is implied by the P^{32} results. Thus over the longer time period, the apparent initial advantage of foliar application may be reduced or lost. The results for total Zn distribution however, suggest that the initial advantage of foliar application demonstrated here may be maintained through to final harvest.

5.4 Discussion

The distribution of total P obtained in this study agrees with that given by Fleming (1973) for three pasture species, ie highest levels in the fruit. Redistribution of P from vegetative parts to the fruit occurs readily in most species (Loneragan et al., 1976; Pate and

TABLE 5-2 Ratios (α) of specific activity of plant parts to the average specific activity of the whole plant for P^{32} and Zn^{65}.

Treatment	leaves	fruit	stems
1	0.345	1.483	0.999
2	1.671	0.551	1.476
3	0.283	1.784	0.784
4	0.244	0.078	4.12

Hocking, 1978; Hocking and Steer, 1983), and this would account for the observed result. Possible reasons for the difference in distribution shown by the α values as compared to those of total P have been mentioned above. This result highlights the need for care when looking at conclusions from short term experiments in the context of a complete growing season.

Both total Zn and Zn^{65} distribution following soil application indicate that Zn is lower in the fruit than in the rest of the tops, and highest in the stems. This is in contrast to results obtained on a wide range of other species (Loneragan and Gladstone, 1967; Fleming, 1973). It has been suggested that differences in absorption and/or translocation may be responsible for differences in susceptibility to Zn deficiency (Loneragan and Gladstone, 1967). If this is the case, then the retention of zinc in the stem that was observed here may explain in part the known susceptibility of Phaseolus beans to Zn deficiency (Viets et al., 1954; Boawn et al., 1969; Barke, 1978).

The mobility of Zn in plants is variable (Bukovac and Wittwer, 1957). At high levels of Zn, retranslocation from mature leaves may occur in appreciable amounts but at low or deficient levels this does not seem to occur (Riceman and Jones, 1958). Thus there could be a level of zinc in the tissue below which redistribution will not occur. If this was the case, foliar applications would need to satisfy this requirement before movement elsewhere in the plant would occur.

For both P and Zn, the foliar application resulted in significant increases in relative isotope concentrations and quantity in the fruit

TABLE 5-3 Recoveries of applied P^{32} in plant parts and distribution within the plants.

treatment	plant	isotope content in plant parts:				
		as % of total in tops			total dpm ($\times 10^5$)	
		leaves	fruit	stems	tops	fruit
1	1	6.1	82.8	11.1	4.1	3.4
(foliar)	2	4.5	86.7	8.8	10.3	8.9
	3	*	*	*	*	*
	4	8.7	64.5	26.8	23.5	15.2
	5	12.3	74,5	13.1	8.0	6.0
	6	15.2	71.8	13.0	5.6	4.1
	7	13.8	70.4	15.8	6.4	4.5
2 (soil)	1	41.4	41.2	17.4	3.4	1.4
	2	39.9	41.5	18.6	15.8	6.6
	3	40.5	37.1	22.4	20.6	7.7
	4	36.4	43.4	20.2	41.2	17.9
	5	37.1	38.5	24.4	75.1	28.9
	6	*	*	*	*	*
	7	*	*	*	*	*

* = missing values

compared to soil application (Tables 5-2, 5-3, 5-4). This is in contrast to the response obtained with S^{35} where relative concentration of isotope was similar in the fruit following foliar and soil uptake.

However, the probable significance of the effect in terms of supply of these nutrients to the whole crop varies. For P, it is possible that the advantage is short-term and thus of little importance in the context of the entire growing period. Sulphur showed no advantage in concentration (table 4-3) and there was no consistent advantage in the actual quantities involved (table 4-2). The Zn results support the conclusion that supply of root absorbed Zn to the fruit may be more restricted than is foliar absorbed Zn. However, in these plants Zn was not deficient, as were the other two nutrients, and there are indications in the literature that movement of Zn from the leaves may be more restricted in a deficiency situation.

Another aspect that must be considered when assessing application of various nutrients to the foliage is the proportion of crop requirements that may be applied in this way. Table 5-5 presents an approximate calculation of the amounts of P, S and Zn that are applied to the leaves from a single spray of a commercial foliar fertilizer at recommended rates. As may be seen, the quantity of P or S supplied will be minimal. Zn on the other hand could be supplied in quantities of some significance in terms of plant requirements even though a proportion of what is retained on the leaf will not be translocated.

These experiments indicate that while an advantage of foliar

TABLE 5-4 Recoveries of applied Zn^{65} in plant parts and distribution within the plants.

treatment	plant	isotope content in plant parts:				
		as % of total in tops			total dpm ($x10^5$)	
		leaves	fruit	stems	tops	fruit
3 (foliar)	1	36.5	58.3	5.2	0.22	0.12
	2	10.3	74.4	15.3	0.68	0.50
	3	14.2	71.5	14.3	0.89	0.63
	4	5.5	78.4	16.1	1.21	0.95
	5	1.5	54.2	39.3	1.15	0.65
	6	1.3	61.3	18.6	0.98	0.74
	7	0.0	99.6	0.4	0.38	0.38
4 (soil)	1	*	*	*	*	*
	2	0.0	0.0	100	0.20	0.0
	3	34.3	16.9	48.8	0.92	0.16
	4	*	*	*	*	*
	5	14.5	0.0	85.5	0.31	0.0
	6	0.0	0.0	100	0.02	0.0
	7	0.0	0.0	100	0.20	0.0

* = missing values

application over soil application in terms of supply to fruit may exist for Zn, for P and S the advantages are less likely to be relevant in terms of crop nutrient requirements. Recent work has indicated that foliar applications of P may have favourable effects on the ability of some plants to withstand certain types of stress (Malakodaiah and Rajeswararao, 1979; Sherchand and Paulsen, 1985). This raises the possibility of effects of foliar sprays other than alleviation of nutrient deficiencies and further investigation into this type of effect is required.

Table 5-5 Quantities of S and P supplied by one application of Complesal 12-2-5 and Zn supplied by one application of multimicro at recommended rates and assuming retention of 5 ml of solution per plant and plant dry weight of 5 g

nutrient	P	S	Zn
content of concentrate % w/v	0.92	0.19	1.45
g/l in 0.2% solution ($x10^{-3}$)	18.4	3.8	29
ug in 5 ml of 0.2% solution	92	19	145
$\mu g\ g^{-1}$ nutrient in healthy plant	4000	4000	30
total in plant	20000	20000	150
1 spray, % of total	0.46	0.46	100

CHAPTER 6

CHAPTER 6

THE CONTRIBUTION OF SPRAY RUNOFF TO PLANT RESPONSES TO NUTRIENT SPRAYS.

6.1 Introduction

A solution that is sprayed onto the foliage of a plant may be absorbed into the plant in two ways: it may be taken up through the leaf surface, or it may run off the leaf onto the soil and subsequently be taken up by the roots. In many field experiments, the degree to which the latter case occurs has not been considered (Garcia and Hanway, 1976; Tayo, 1981; Shawa, 1982a). Thus the responses obtained in these situations to foliar sprays could well be due to the simultaneous application of a source of soluble nutrients to the roots.

When considering foliar fertilizers different types of responses may be monitored, including growth responses such as dry weight increases, and physiological responses such as changes in the level of photosynthesis or related factors. Work by Malakondaiah and Rajeswararao (1979) on salt stressed peanuts indicated that foliar sprays of phosphate increased chlorophyll levels in both stressed and unstressed plants. Thus chlorophyll levels are a comparatively easily measured parameter that might be expected to show some response to foliar sprays.

In this experiment, an attempt was made to assess the degree to which responses to foliar fertilizers could be attributed to the uptake of spray runoff by roots. Responses investigated included changes in dry weight of the shoot system (tops), and changes in the chlorophyll levels in the leaves. An assessment of the quantities that could be retained by the foliage was also undertaken.

6.2 Methods

Seeds were germinated in sand and transplanted after one week into 11cm pots containing 1 kg of washed sand. Cotyledons were removed after germination and 15 cm^3 nutrient solution (Middleton and Toxopeus, 1973) supplied per day. This low level of nutrient supply was maintained in order to maximise response to the fertilizer treatments.

Chlorophyll measurements were made every three days from the time the stem straightened after germination till harvest. Measurements were done on one primary leaf and four trifoliate leaves on successive nodes, thus giving a range of maturity stages at any one time. A portable chlorophyll meter was used, as described by Hardacre et al. (1984). The meter was calibrated for beans by cutting 21 mm diameter discs from the leaves, taking a reading with the meter and then determining chlorophyll content by acetone extraction. This involved grinding the disc of leaf tissue with sand and 4 cm^3 of acetone containing 25g/l $MgCO_3$. This was then filtered through sintered glass and the filtrate made up to a standard volume. Absorbance at 645 and 543 nm was read on a spectrophotometer and chlorophyll calculated from the equation:

Total chlorophyll = 8.02 A543 + 20.2 A645 (Arnon, 1949)

The figures obtained were fitted to the basic calibration curve given by Hardacre et al. (1984), with a calibration constant of 1.3 (figure 6-1).

At seven weeks the fertilizer treatments were applied. A randomised complete block design was used with 5 replicates/treatment in each of two blocks. Treatments were;

1- Application of 10 cm^3 of 0.2% Complesal 12-2-5 solution by spraying onto the foliage.

2- Application of 10 cm^3 of 0.2% Complesal 12-2-5 solution by spraying onto the foliage with provision for collection of spray runoff.

3- Application of 10 cm^3 of 0.2% Complesal 12-2-5 solution to the soil (sand).

4- Application to the soil of the runoff collected from treatment 2.

5- (control) Spray with 10 cm^3 distilled water.

Several plants received no treatments but from the time of treatment application received double quantities of nutrient solution

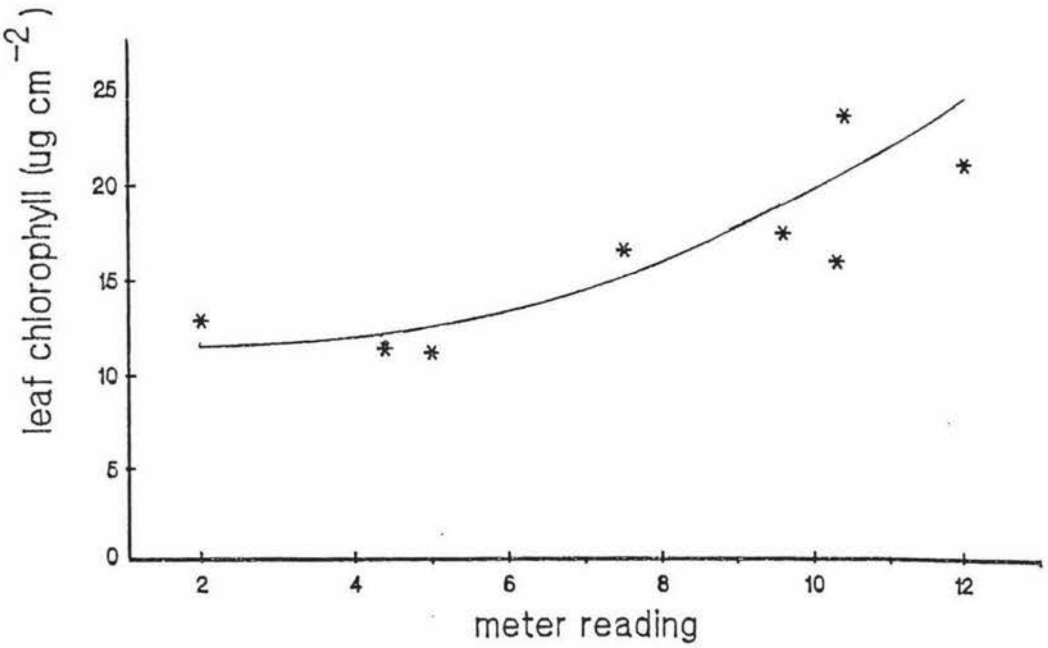

Figure 6-1 Chlorophyllometer calibration curve for Phaseolus vulgaris grown under glasshouse conditions (high range setting). Scale factor = 1.3

(ie, $30cm^3$/day). This was of the order of 50 - 70 times the extra nutrient that was applied in the treatments.

The treatments were applied twice, one week apart, and the plants harvested one week after the second application. The applications for the two blocks were separated in time, the second block receiving treatments three days after the applications to the first block. At the harvest of the second block, the plants were used for estimations of solution retention. This was done by dipping the weighed tops into a solution of Complesal, after which the plants were left for five minutes, given one sharp jolt and reweighed. Fresh weights and leaf area measurements were done on these plants, and dry weights were taken for all plants. A Licor LI-3100 area meter was used for leaf area determinations.

6.3 Results

The dry weight results are given in table 6-1. There was a slight trend for treatment 3 to yield the highest dry weight, however this was not significant and no other differences between treatments were observed. Examination of the chlorophyll data indicated that all trifoliate leaves followed a similar pattern over the time of measurement. This seemed to be virtually independent of leaf age. Thus the results for the first trifoliate leaf will be discussed here as being representative of trends in the plant and covering the longest time period.

TABLE 6-1 Dry weights of tops (g)

		treatment					
block	replicate	1	2	3	4	5	plants recieving increased nutrient supply to roots.
1	1	8.91	9.19	9.52	8.36	8.85	9.38
	2	8.93	8.74	9.22	8.37	9.30	10.12
	3	8.48	9.23	8.89	8.99	8.70	
	4	7.88	8.53	9.48	9.00	8.69	
	5	8.88	8.87	8.14	8.51	8.99	
	mean	8.62	8.92	9.05	8.65	8.91	
2	1	9.40	9.52	10.40	9.83	9.30	10.88
	2	9.65	9.28	10.58	9.37	9.58	10.07
	3	10.02	0.00	9.35	8.65	8.99	
	4	9.32	9.62	9.74	9.23	9.30	
	5	10.16	9.31	10.53	9.11	9.83	
	mean	9.71	9.55	10.12	9.24	9.80	

The chlorophyll levels in the first trifoliate leaf averaged within blocks are shown in figure 6-2. No differences were observed between treatments. In addition there was no separation in time of the fluctuations in chlorophyll in a manner analogous to the separation of the application between blocks, and fluctuations occurred both before and after applications were made. These observations indicate that factors other than the treatments were responsible for the fluctuations observed. Comparison with relative humidity and temperature data (figures 6-3, 6-4) suggests that climatic factors may be involved. Peaks in chlorophyll levels (days 7, 31, 41) seemed to follow days with comparatively high minimum relative humidity (>50%) and low maximum temperature (<30 °C), ie days 6, 26 ,39.

Retention of spray as functions of leaf area and leaf fresh weight are shown in figures 6-5 and 6-6. Leaf fresh weight was a slightly better predictor of retention (r=0.78) than was leaf area (r=0.76).

6.4 Discussion

The lack of significant differences in dry weights between treatments 1-4 and the control (treatment 5) indicates that either these plants were not responsive to fertilizer application or that dry weight was not a sensitive enough parameter to show any responses to these treatments. The additional plants which had received larger applications of nutrient solution to the roots had slightly higher dry weights than did any of the treatments which suggests that the treated plants may have shown a response to higher levels of nutrient or to

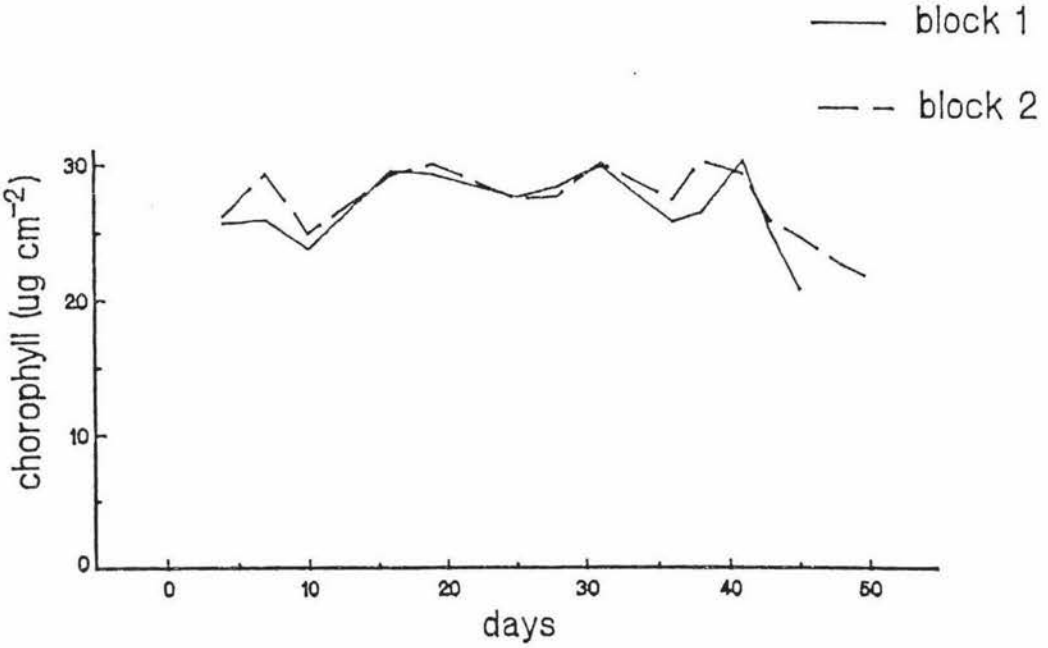

Figure 6-2 Chlorophyll levels in the first trifoliate leaf over the growing season. Data averaged over treatments and replicates.

application over a longer time period. Thus any further work on this type of system would be improved by extending the time period to include, for example, an entire growing season, or period of pod development.

The suggested influence of climatic conditions on chlorophyll levels could be due to either direct or indirect effects. Indirect effects involve the possible influence of mild transient water stress over the midday period on chlorophyll levels. Chlorophyll development in etiolated tissue can be sensitive to quite small water deficits (Virgin, 1965; Bourque and Naylor, 1971), but to what degree this sensitivity extends to more mature tissue seems in doubt (Alberte et al., 1975). Mild water stress seems to reduce the content of chlorophyll protein complex (Alberte and Thornber, 1977) but it was not clear in that study whether the reduction was due to reduced development or increased degradation of the complex. Much of the work that has been done on the effects of water stress on chlorophyll deal with stress over a longer time period than is the case here and so it is not certain how much influence short term stress periods may have in this respect.

Possible direct effects of climatic conditions on chlorophyll levels would involve the destruction of chlorophyll that occurs under conditions of high light and temperature (Powles, 1984). Light was not measured in this experiment, however as there was no shading in the glasshouse, high light levels were likely to be reached on days where the temperature was high. These, coupled with the high temperatures that were measured, could result in photo-oxidative conditions over the

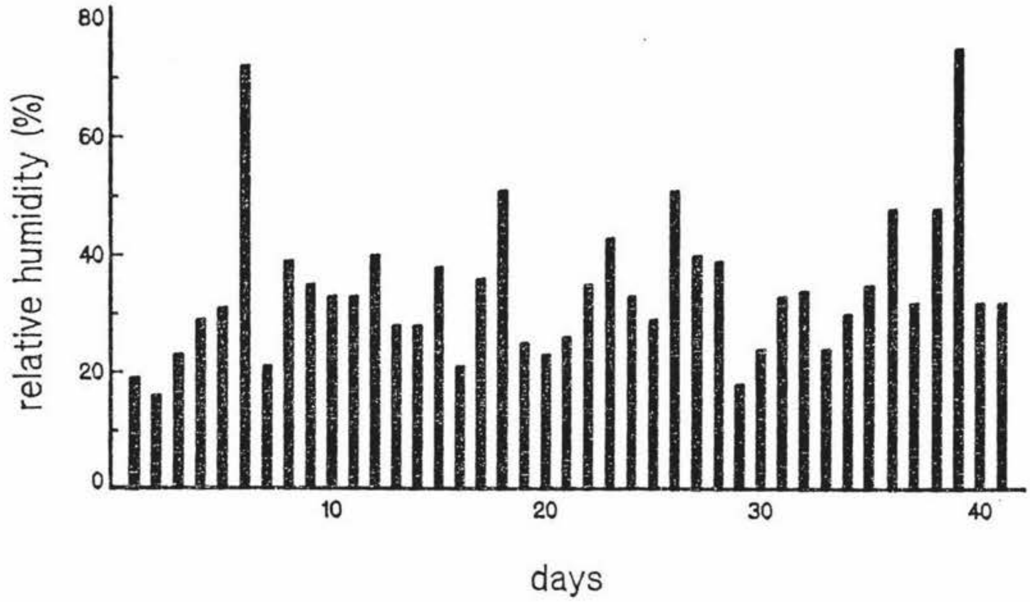

Figure 6–3 Minimum day humidity over the growing period.

midday period for most days. If this is the case, the more mild conditions that prevailed on days 6, 26, and 39 could result in reduced breakdown and slight increases in total chlorophyll levels. It is not possible to differentiate between temperature effects and effects on water relations as they both contribute to a stress situation.

The retention of sprays is an important aspect of foliar application of nutrients to plants in that it is a major determinant of the quantities that can be supplied in this way. Tables 6-2 and 6-3 give approximate estimates of the quantities of nutrients that can be supplied by one spray of complesal 12-2-5 and multimicro respectively. For the calculation a leaf fresh weight of 20g and a whole plant dry weight of 9.6g was assumed. The spray retention figure of 7g was calculated from the regression equation for retention on leaf fresh weight, i.e. retention = 0.7 + 0.313 leaf fresh weight. Figures for the nutrient requirement for bean are from Barke (1978).

As may be seen, the quantities of macronutrients that may be applied under these circumstances are only minimal in relation to plant requirements, but the quantities of micronutrients may be a significant proportion of requirements. This supports the conclusion that in terms of supply of nutrients, foliar fertilization is likely to have its greatest application in supply of micronutrients. Use of the technique with macronutrients is likely to be of value only under special circumstances (see chapter 2), if at all.

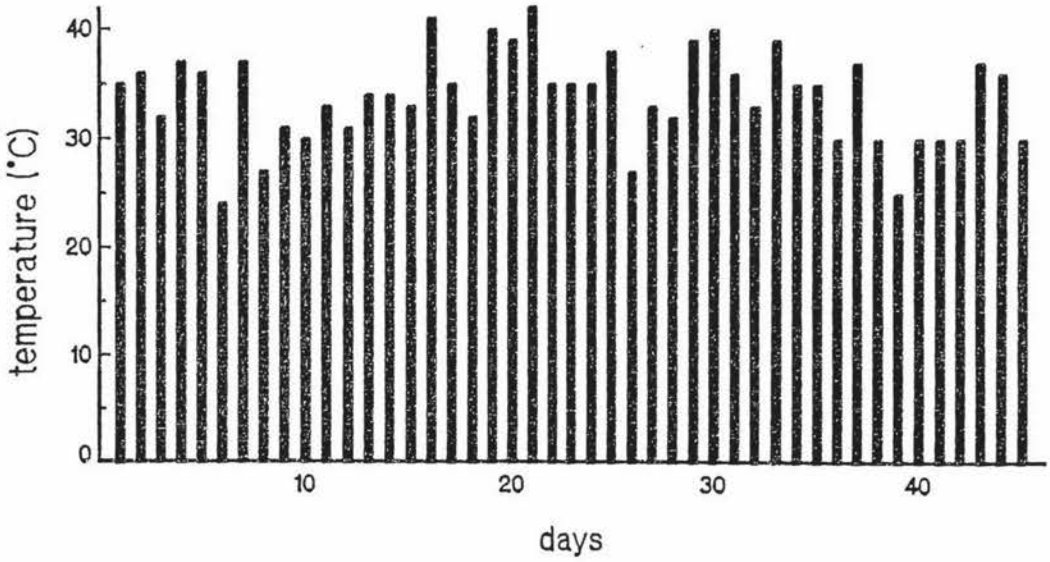

Figure 6-4 Maximum day temperature over the growing period.

Table 6-2 Estimate of the nutrient that can be supplied to the surface of the leaf in a single application of Complesal 12-2-5 solution, as a proportion of the total plant requirements.

	Plant		nutrient	
Element	content ($\mu g\ g^{-1}$)	requirement in 9.6 g dry weight (μ g)	in 7g of 0.2% solution (μg)	proportion of requirements supplied (%)
N	500000	480000	1670	0.35
P	4000	38400	106	0.28
K	20000	192000	579	0.30
S	4000	38400	22	0.06
Mg	4000	38400	17	0.04
B	25	240	3	1.25
Cu	5	48	1.4	2.92
Fe	100	960	1.4	0.15
Mn	50	480	1.4	0.29
Zn	30	288	0.7	0.24

Table 6-3 Estimate of the nutrient that can be supplied to the surface of the leaf in a single application of Complesal multimicro solution, as a proportion of the total plant requirements.

Element	supply in 7g of 0.2% solution (μg)	plant requirement (μg g^{-1})	supply as proportion of required(%)
B	42	240	17.5
Fe	153	960	15.9
Cu	70	48	100
Mn	209	480	43.5
Zn	153	288	53.1
Mg	284	38400	0.7
S	738	38400	1.9

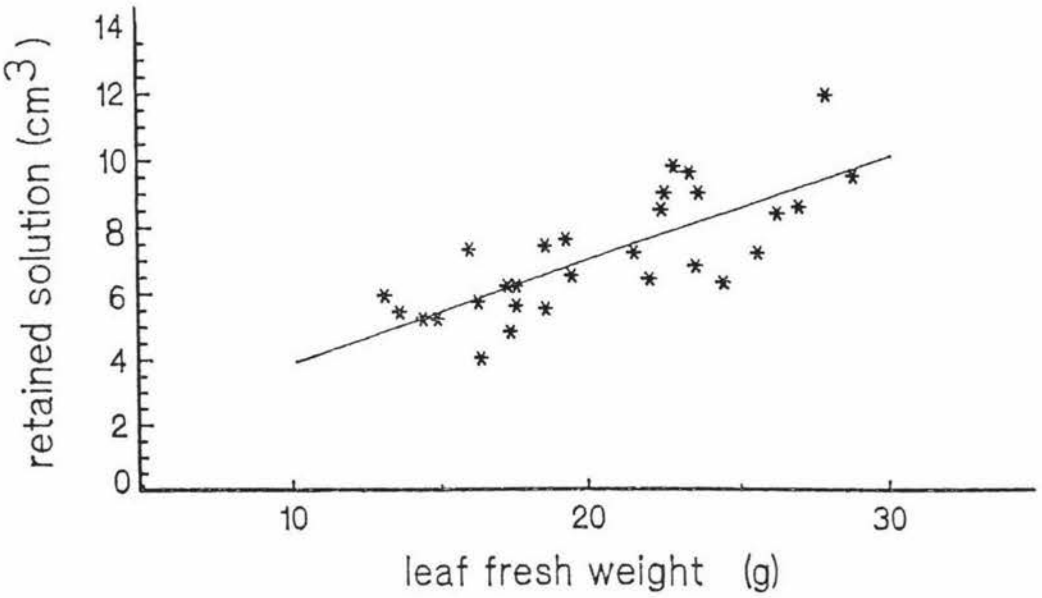

Figure 6–5 Retention of Complesal solution on <u>Phaseolus vulgaris</u> as a function of leaf fresh weight. (r=0.76)

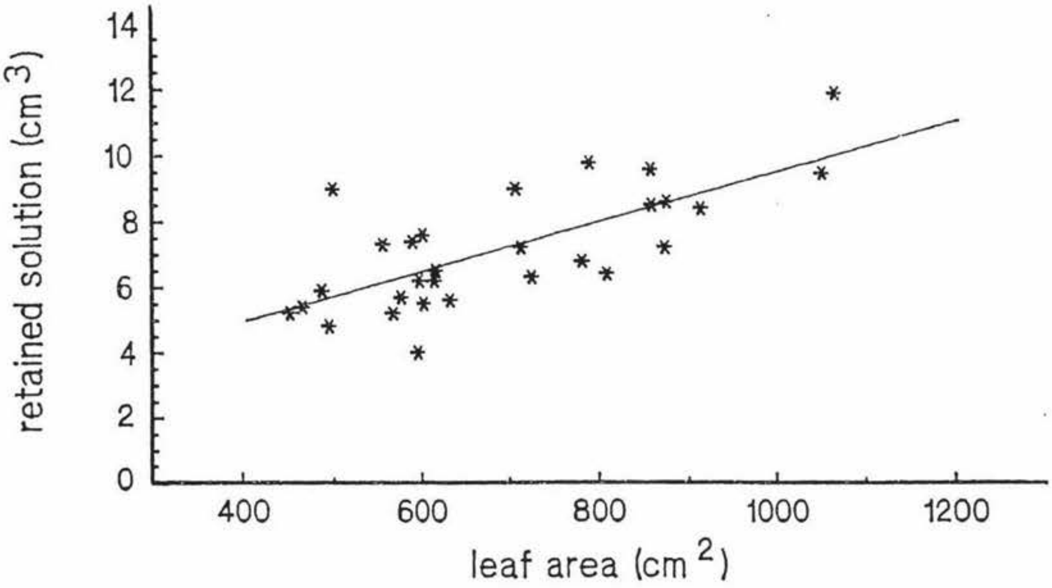

Figure 6-6 Retention of Complesal solution on <u>Phaseolus vulgaris</u> as a function of leaf area. (r=0.78).

CHAPTER 7

CHAPTER 7

EFFECT OF FOLIAR SPRAYS ON THE UPTAKE OF P^{32} BY THE ROOTS.

7.1 Introduction

There is little doubt that under certain conditions, nutrients can be absorbed by leaves (Bukovac and Wittwer, 1960; Kannan, 1980; see also results ch 4 and 5). Such uptake is likely to alter the balance of nutrients in the plant. Since uptake by roots is dependent to some extent on metabolic demand for nutrients (Russell, 1977), such alterations in nutrient balance may have an effect on root absorption.

These effects were investigated by Thorne (1955; 1957; 1958) who found that application of nutrients to the leaves resulted in changes in the uptake by roots of both the nutrient applied and other nutrients. Root uptake of phosphate was found to be increased by spraying with nitrogen or potassium, but could be decreased by phosphate sprays. Results of this kind may have considerable implications in terms of efficiency of fertilizer use, either increasing or decreasing utilization of soil resources and soil-applied fertilizers.

This experiment aimed to investigate the effects of a complete nutrient solution applied to the foliage on the exploitation of soil resources by the roots. Such exploitation has two aspects: root growth and proliferation in the soil volume and efficiency of uptake of nutrients within that volume.

Phosphate was used in this experiment because it is not very mobile in the soil and, therefore, proliferation in the soil volume by the root system is an important aspect of phosphate supply to the plant.

7.2 Method

Seeds were germinated and planted out in 700 cm^3 pots containing approximately 500g of soil (section 3.1). At eight weeks they were transplanted into 17 cm pots with an outer layer of soil labelled with P^{32} (figure 7-1). Each pot contained one plant.

Soil was labelled by adding 0.59 μCi P^{32} per g air-dry soil as a 17.7 $\mu Ci/cm^3$ solution and shaking for four hours. Each pot contained 900g of this soil as a 1cm layer around the outside and base plus 1100g of unlabelled soil, giving a total of 2.5 kg after transplanting.

Several pots were left unlabelled to give control plants for use in the measurement of background radiation during the counting of P^{32}.

The plants were grown in a glasshouse with the temperature maintained in the range 19-25 °C. No fertilizers were added to the soil apart from the treatments listed below.

Three foliar treatments were applied to the plants with 10

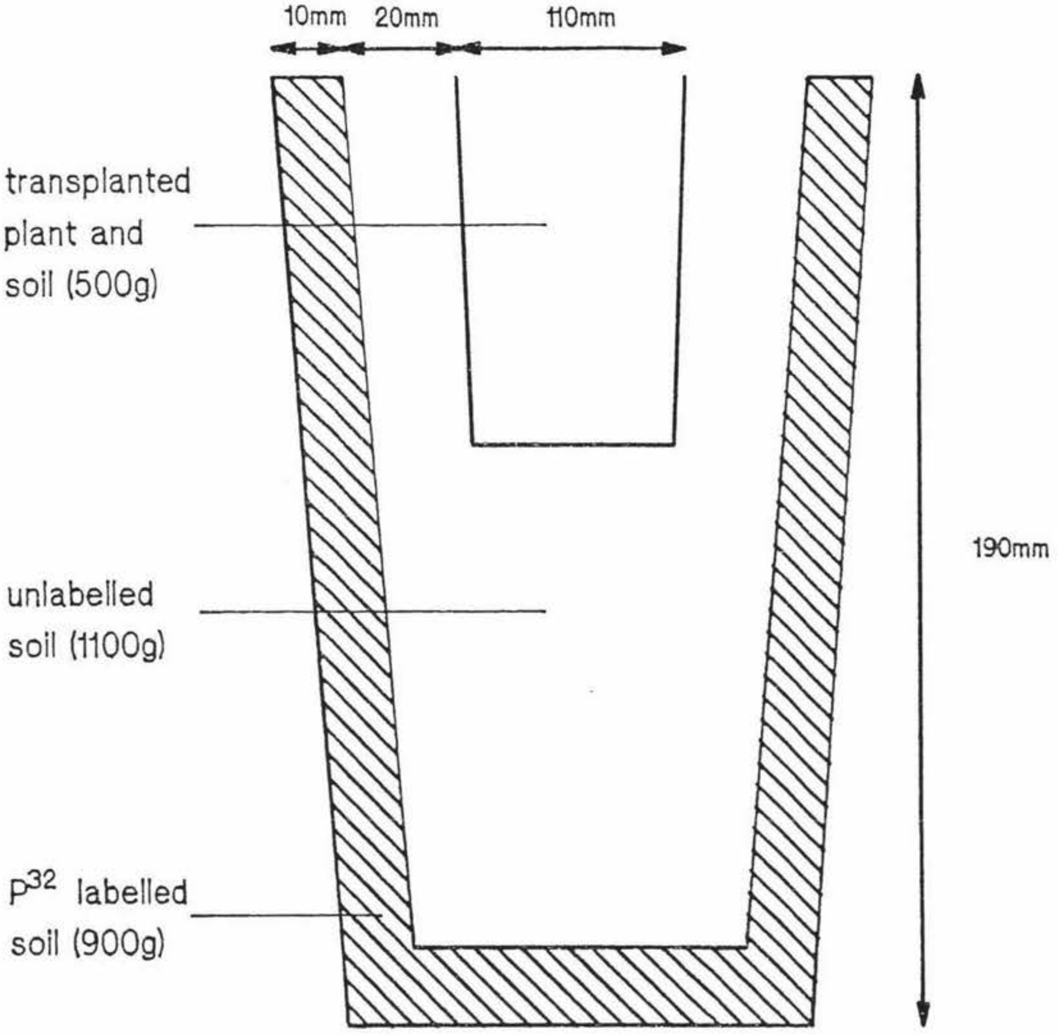

Figure 7–1 Diagram of pot showing position of labelled soil at time of transplanting.

replicates per treatment:

1. No sprays
2. Sprayed with distilled water
3. Sprayed with 2% Complesal 6-5-5 solution

Spraying was carried out as described in section 3.2.(i) with provision for prevention of runoff into the pot. Two sprays were applied, the first at time of transplanting, and the second one week later.

The plants were harvested one week after the second spray. Tops were dried and dry weights measured. Total N and P were determined by acid digestion followed by autoanalysis (section 3.4.2) and P^{32} activity by Cherekov counting (section 3.5.2).

Roots were extracted for three replicates of treatments 1 and 3 by dry extraction. Root length determinations were done by the intersection method as described by Bohm (1979).

7.3 Results

Results for the analysis of plant tops may be seen in 'able 7-1. There was a significant increase in activity in sprayed plants as compared to unsprayed plants (table 7-2). This indicates that there was a significant effect of spraying on root uptake of the labelled phosphate over the two week period. However, there was no difference between treatment 2 and 3, i.e. the nutrient and water sprays. This

Table 7-1 Analysis of plant tops.

Treatment	dry weight (g)	total N ($\mu g\ g^{-1}$)	total P ($\mu g\ g^{-1}$)	specific activity P^{32} (dpm μg^{-1})
1 no spray	1.78 (0.49)	31562 (2278)	2277 (257)	8.93 (5.39)
2 water	1.73 (0.52)	31256 (2945)	2251 (157)	13.89 (5.86)
3 complesal	1.73 (0.27)	31757 (2083)	2432 (253)	11.97 (3.57)

( ) = standard deviation

would imply that the effect obtained is not related to nutrient uptake by the foliage.

Both total nitrogen and phosphorus levels are low compared to those given by Barke (1978) for the youngest mature leaf at early flowering, ie 50 000 μg g^{-1} nitrogen and 4000μg g^{-1} phosphorus. While the results obtained for overall average levels in the plant may be expected to be lower than for the youngest mature leaf, these figures do indicate a probable deficiency situation.

The slight increase in the value for total P with treatment 3 can be accounted for by considering the quantity of phosphate retained on the foliage from the sprays. This was approximately 352 μg phosphate, which is enough to give the difference obtained.

No significant differences were found in either root weight or root length (table 7.3).

7.4 Discussion

The positioning of the label around the edges of the pot meant that labelled phosphate was not available to the plant immediately after transplanting. This would have the effect of emphasising any effect of differing root growth rates, as faster growing root systems would tend to start exploiting the labelled soil first. The difference obtained here in isotope content of sprayed and unsprayed plants indicates that the root systems of sprayed plants either proliferated to a greater

Table 7-2 ANOVA for response to spraying

	df	ss	ms	F
treatment	1	106.7	106.7	4.25$^{\alpha}$
error	28	701.9	25.1	

α= significant at the 5% level

Table 7-3 Dry weights and root length estimates for sprayed and unsprayed plants (average of three replicates).

Treatments	dry weight (g)	root length (cm)
1 no spray	0.4110	5570
3 complesal	0.4535	5805

extent through the soil volume or were more efficient at uptake. The measurements of root dry weight, root length and total phosphate in the plant might have been expected to throw some light onto the question of which of these two aspects (if either) is more important, as increased root proliferation would increase dry weight and length of roots, and increased uptake efficiency would alter total phosphate. However, the variability in determination of these figures was very high, indicating that these parameters are not sensitive enough to show significant responses to these treatments over a time period of two weeks.

It is often concluded, when a growth response is obtained to application of nutrient sprays, that such responses must be due to the nutrient content of the sprays (eg Sato, 1971; Garcia and Hanway, 1976; Sesay, 1978). While this may often be the case, the results obtained here indicate that other factors may need to be considered, as no response was obtained with the nutrient spray compared to water. This is in contrast to results obtained by Thorne (1955; 1958) who found marked differences in root uptake with foliar sprays to swedes compared to a control of water sprays. However in Thornes' experiments the plants were sprayed six times a week for six weeks with a 0.1M solution. This would result in a considerably greater supply of nutrient than the treatment applied here, i.e. two sprays of a more dilute solution (see table 6-2). The recommendations for the foliar sprays are to spray in conjunction with pesticides as a 0.1-0.2% solution, so the application rates used in the experiment reported here are more relevant to most field situations.

The response that was found in this study to spraying with water implies a connection with the water relations of the plant. The conditions under which the plants were grown, ie a heated glasshouse, may have resulted in periods of mild water deficits in the leaves, of the order of 3-4 bar. While this would not be enough to affect metabolic processes such as photosynthesis (Boyer, 1970), it could have a marked effect on leaf growth. Very minor reductions in leaf water potential may reduce leaf enlargement to a considerable degree. Boyer (1970) found that leaf expansion was reduced by up to 25% by leaf water potentials of -4 bars in maize, soybean and sunflower. Since rates of leaf enlargement are most rapid at potentials in the range -1.5 to -2.5 bar (Boyer and McPherson, 1975), this constitutes a very rapid decline in growth with decreases in water potential.

Such drastic decreases in leaf growth could also affect root uptake of nutrients. In a study on phosphate uptake by oats, Williams (1948) concluded that the rate of uptake was dependent to a considerable degree on the metabolic requirement for phosphate. A correlation between uptake and relative growth rate has been found for other nutrients (Sutcliffe, 1976). Thus reductions in leaf growth may have adverse effects on P uptake. This would result in low levels of P in the plant as were obtained here. If such a situation was the case, the spraying of the plants would correct the deficit for a period of time resulting in increased uptake. Chu (1979) quotes several examples of overhead sprinkling during the day resulting in increased yields.

The results of this experiment show that foliar spraying can have a significant effect on root exploitation of soil resources, although it is not possible in this case to determine whether this was due to increased root growth or more efficient uptake. At the rates and frequency of application used in this study, no result was found that could be attributed to foliar nutrient uptake. Thus the increase in use of soil resources seems in this case to be connected to aspects of plant water relations. It is possible that more frequent sprays may result in a significant effect, however the practical aspects of frequent applications to a crop must be considered. Daily applications are only feasible in a crop situation if there are existing facilities for spray application such as a spray irrigation system.

In terms of water requirement, this experiment suggests the desirability of periods during which relative humidity is high to minimise periods of mild water stress. This is likely to be of less importance in most outdoor situations as humidity usually increases at night. For crops grown in temperature controlled glasshouses however, the role of such stresses may be worth further investigation.

CONCLUSION

CHAPTER 8

CONCLUSION

The results of the isotope distribution experiments (chapters 4 and 5), suggest that for some ions at least, foliar-applied nutrients may be transported to the fruit of Phaseolus vulgaris more efficiently than are root absorbed nutrients.

However, this increase in efficiency of utilization may not necessarily result in increased efficiency of fertilizer use as interactions with plant physiology and supply considerations must be taken into account.

The quantities that may be supplied by foliar and soil application of fertilizer differ considerably. Spray retention figures for Phaseolus (chapter 6) indicate that only if plant requirements for a nutrient are low at the time of application will foliar application be able to supply significant proportions of those requirements. Situations where this is the case include the application of micronutrients and perhaps some macronutrients at a particular stage of development. In the latter case the supplementary nature of the foliar applications needs to be stressed, soil applications still being necessary to supply the total requirements of the plants.

Interactions also affect fertilizer efficiency. Foliar applications may increase, decrease or have no effect on root uptake of nutrients. If root uptake is decreased, overall supply to the fruit may be less or the same as would be the case following soil application. In this case, an apparent advantage in fertilizer utilization as observed in isotope distribution experiments, would not result in any advantage in total supply to the fruit. In this study, no effect on root uptake of P^{32} was observed from nutrient applications to the leaves.

Another consideration in foliar application that was emphasised by the results obtained in this study, was the effect of the water in which the nutrients are carried. In terms of the plants' water requirements, the quantities of water are probably negligible. However, during, and for a short time following, spraying, relative humidity around the plant is much increased. This may result in a decrease in the internal water deficits of the leaves.

That this may affect the uptake of nutrients by the roots is indicated by the increased uptake of P^{32} following water sprays (chapter 7). It is also clear from the literature that high humidities may favour foliar uptake. In addition to this, humid conditions favour stomatal opening which may result in increased CO_2 fixation and subsequent carbohydrate production.

The separation of such effects resulting from the application of water around the shoot system is a factor that should be considered in further work on foliar fertilizers, as water is cheaper to apply than are nutrient solutions.

SUMMARY

SUMMARY

1- A review of the literature indicated that, while a considerable body of information is available on the physiological aspects of uptake and utilization of foliar-applied nutrients, this has seldom been adequately considered in design or interpretation of field assessments of foliar fertilizers. The characteristics of the test crop, the climate and the nutrient applied all affect the potential response from both root and foliar-applied fertilizers, and this needs to be taken into account when evaluating foliar fertilization either as a technique in general or in a specific set of circumstances.

2- The distribution of S^{35}, P^{32} and Zn^{65} were compared following application of these isotopes separately to the soil and foliage of Phaseolus vulgaris. For P^{32} and Zn^{65}, a greater proportion of foliar-applied isotope was translocated to the developing fruit than was the case for soil-applied isotope. It was concluded however that the practical implications of these results in terms of efficiency of fertilizer use probably varied with translocation characteristics of the particular nutrient in the plant. S^{35} showed no advantage in total movement to the fruit, but differences in distribution between fruit at different positions on the plant, did result from uptake by roots as compared to uptake by foliage.

3- The contribution of spray runoff to responses obtained with foliar fertilizers was investigated with a commercial foliar spray (Complesal 12-2-5) on Phaseolus vulgaris. Dry weights were used to indicate response. It was concluded that dry weight was not a sensitive enough parameter to show responses to the applied treatments over the time period of the experiment.

4- Retention of the Complesal solution on Phaseolus vulgaris was measured in conjunction with the measurements of spray runoff. Both leaf fresh weight and leaf area showed a positive correlation with spray retention.

5- The effect of Complesal sprays on chlorophyll contents in the leaves of Phaseolus vulgaris was investigated using a portable photometer. Environmental factors were found to have considerable effects on chlorophyll levels in the leaves. No effect of nutrient sprays was observed.

6- Foliar sprays were found to increase root uptake of P^{32} from labelled soil. This seemed to be due to effects on water relations of the plants rather than nutrient supply as sprays of distilled water had a similar effect to nutrient sprays.

7- Further research is required in the area of interactions of foliar fertilizers with general plant physiology and root uptake. In addition, work assessing crop responses to foliar fertilizers needs to be focussed on specific situations where foliar fertilizers might be expected to show an advantage over soil applications. Examples of such situations may be under conditions of low soil temperatures, and in situations where regular and frequent sprays are possible.

BIBLIOGRAPHY

BIBLIOGRAPHY

ALBERTE, R.S. AND THORNBER, J.P. (1977) Water stress effects on the content and organization of chlorophyll in mesophyll and bundle sheath chloroplasts of maize. PLANT PHYSIOLOGY 59:351-353

ALBERTE, R.S., FISCUS, E.L. and NAYLOR, A.W. (1975) The effects of water stress on the development of the photosynthetic apparatus in greening leaves. PLANT PHYSIOLOGY 55:317-321

ALSTON, A.M. (1979) Effects of soil water content and foliar fertilization with nitrogen and phosphorus in late season on the yield and composition of wheat. AUSTRALIAN JOURNAL OF AGRICULTURAL RESEARCH 30:577-585

ARNON, D.I. (1949) Copper enzymes in isolated chloroplasts PLANT PHYSIOLOGY 24:1-15

ARNON, D.I., FRATZE, W.E. and JOHNSON, C.M. (1942) Hydrogen ion concentration in relation to absorption of inorganic nutrients by higher plants PLANT PHYSIOLOGY 17:515-524

ASHOUR, N.I. and THALOOTH, A.T. (1983) Effect of soil and foliar application of nitrogen during pod development on the yield of soybean (Glycine max. Merr.) plants. FIELD CROPS RESEARCH 6:261-266

BAKER, E.A. and HUNT, G.M. (1981) Developmental changes in leaf epicuticular waxes in relation to foliar penetration. NEW PHYTOLOGIST 88:731-747

BANKS, L.W. (1982) Effects of timing of foliar zinc fertilizer on yield components of soybeans. AUSTRALIAN JOURNAL OF EXPERIMENTAL AGRICULTURE AND ANIMAL HUSBANDRY 22:226-231

BARAT, C.K., and DAS, N.B., (1962) Soil and foliar application of urea and superphosphate. INDIAN JOURNAL OF AGRICULTURAL SCIENCE

BAREL, D. and BLACK, C.A. (1979) Foliar application of P: I. Screening of various inorganic and Organic P compounds. AGRONOMY JOURNAL 71:15-21

BARKE, R.E. (1978) Mineral nutrition of french bean In relation to bean seed quality. pp 13-28 In: PROCEEDINGS OF BEAN IMPROVEMENT WORKSHOP, SYDNEY

BARRIER,G.E. and LOOMIS,W.E. (1957) Absorbtion and translocation of 2,4-dichlorophenoxyacetic acid and P32 by leaves. PLANT PHYSIOLOGY 32:225-231

BATJER, L.P. and THOMPSON, A.H. (1949) Effect of boric acid sprays applied during bloom upon the set of pear fruits. PROCEEDINGS OF THE AMERICAN SOCIETY OF HORTICULTURAL SCIENCE 53:141-142

BELESKY, D.P. and JUNG, G.A. (19??) Seasonal variation of water soluble and total zinc in cool season grasses. AGRONOMY JOURNAL 74:1009-1012

BIDDULPH, O., CORY, R. and BIDDULPH, S. (1956) The absorption and translocation of sulfur in red kidney bean. PLANT PHYSIOLOGY 31:28-33

BIDDULPH, O., BIDDULPH,S., CORY, R., KOONTZ,H., (1958) Circulation patterns for phosphorus, sulphur and calcium in the bean plant. PLANT PHYSIOLOGY 33:293-300

BIDWELL, R.G.S., (1979) PLANT PHYSIOLOGY 2nd ed. McMillan Publishing Co. Inc.

BIELESKI, R.L. and FERGUSON, I.B. (1983) Physiology and metabolism of phosphate and its compounds. pp 422-499 In: ENCYCLOPEDIA OF PLANT PHYSIOLOGY. NEW SERIES v15A ed. A. Lauchli and R.L. Bieleski. Springer-Verlag.

BOAWN,L.C., RASMUSSEN. P.E., BROWN,J.W., (1969) Relationship between tissue zinc levels and maturity period of field beans. AGRONOMY JOURNAL 61:49-51

BOHM, W. (1979) METHODS OF STUDYING ROOT SYSTEMS. Ecological studies v.33 Springer-Verlag.

BOLLARD, E.G. (1970) The physiology and nutrition of developing fruits. pp387-425 In: THE BIOCHEMISTRY OF FRUITS AND THEIR PRODUCTS ed. A.C. Hulme Academic Press.

BONAS, U., SCHMITZ, K., RENNENBERG, H., BERGMANN, L. (1982) Phloem transport of sulphur in Ricinus. PLANTA 155:82-88

BOOTE,K.J., GALLIHER, R.N., ROBERTSON, W.K., HINSON,K., HAMMOND, L.C. (1978) Effect of foliar fertilization on photosynthesis, leaf nutrition and yield of soybeans. AGRONOMY JOURNAL 70:787-791

BOURQUE, D.P. and NAYLOR, A.W. (1971) Large effects of small water deficits on chlorophyll accumulation and ribonucleic acid synthesis in etiolated leaves of jack bean (Canavalia ensiforrmis L. DC.) PLANT PHYSIOLOGY 47:591-594

BOUMA, D., (1969) The response of subterranean clover (Trifolium subterraneumL.) to foliar applications of phosphorus. AUSTRALIAN JOURNAL OF AGRICULTURAL RESEARCH 20:435-445

BOUMA, D., (1975) The uptake and translocation of sulphur in plants. pp79-86 In: SULPHUR IN AUSTRALASIAN AGRICULTURE ed. K.D. McLachlan Sydney University Press.

BOYER J.S. (1970) Leaf enlargement and metabolic rates in corn, soybean, and sunflower at various leaf water potentials. PLANT PHYSIOLOGY 46:233-235

BOYER, J.S. and McPHERSON, H.G. (1975) Physiology of water deficits in cereal crops. ADVANCES IN AGRONOMY 27:1-23

BRAMLAGE, W.J., DRAKE, M. and LORD, W.J. (1980) The influence of mineral nutrition on the quality and storage performance of pome fruits grown in North America. pp29-39 In: MINERAL NUTRITION OF FRUIT TREES. ed D. Atkinson, J.E. Jackson, R.O. Sharples and W.M. Waller. Butterworths.

BROWN, L.C. (1971) Determination of phosphorus-32 and -33 in aqueous solution.ANALYTICAL CHEMISTRY 43:1326-1328

BUKOVAC, M.J. AND WITTWER,S.H. (1957) Absorbtion and mobility of foliar applied nutrients. PLANT PHYSIOLOGY 32:428-434

BUKOVAC, M.J. AND WITTWER,S.H. (1960) Absorbtion and distribution of foliar applied mineral nutrients as determined with radioisotopes pp215-230 In: PLANT ANALYSIS AND FERTILISER PROBLEMS ed. W. Reuther Lord Baltimore Press

CANTLIFFE,D.J. and WILCOX, G.E. (1972) Effect of surfactant on ion penetration through leaf wax and a wax model. JOURNAL OF THE AMERICAN SOCIETY OF HORTICULTURAL SCIENCE 97:360-363

CHU, A.C.P. (1979) Aspects of water deficit and vegetative growth in selected pasture and forage grasses. PhD thesis Massey University

COOK, J.A. and BOYNTON, D., (1952) Some factors affecting the absorption of urea by McIntosh apple leaves. PROCEEDINGS OF THE AMERICAN SOCIETY OF HORTICULTURAL SCIENCE 59:82-90

COWIE, J.D. (1978) Soils and agriculture of Kairanga county, North Island, New zealand. NEW ZEALAND SOIL BUREAU BULLETIN 33

DATTA, N.P. and VYAS, K.K., (1967) Uptake and utilization by maize from foliar sprays. pp371-375 In: ISOTOPES IN PLANT NUTRITION AND PHYSIOLOGY Proceedings of symposium 1966 IAEA/FAO

DURING, C. (1984) FERTILIZERS AND SOILS IN NEW ZEALAND FARMING. Hasselberg.

FISHER, E.G. and COOK, J.A. (1950) Nitrogen fertilization of the M^{c}Intosh apple with leaf sprays of urea. II. PROCEEDINGS OF THE AMERICAN SOCIETY OF HORTICULTURAL SCIENCE 55:35-40

FISHER, E. BOYNTON, D. and SKODVIN, K. (1948) Nitrogen fertilization of the M^{c}Intosh apple with leaf sprays of urea. PROCEEDINGS OF THE AMERICAN SOCIETY OF HORTICULTURAL SCIENCE 51:23-32

FLEMING, G.A., (1973) Mineral composition of herbage pp529-566 In CHEMISTRY AND BIOCHEMISTRY OF HERBAGE V1 ed. C.W. Butler and R.W. Bailey Academic Press

FORD, E.M., WHITE, G.C. and ALLEN, M. (1965) The response of magnesium-deficient Edward VII apple trees to variations in the timing and composition of foliar sprays. JOURNAL OF HORTICULTURAL SCIENCE 40:351-360

FRANKE, W. (1961) Ectodesmata and foliar absorption. AMERICAN JOURNAL OF BOTANY 48:683-691

GANE, A.J., KING, J.M. and GENT, G.P. (1975) Pea and bean growing handbook. V2 Beans Processors and growers research organisation.

GARCIA,R.L. and HANWAY, J.J. (1976) Foliar fertilization of soybeans during the seed-filling period. AGRONOMY JOURNAL 68:653-657

GRUNDON, N.J., (1980) Effectiveness of soil dressings and foliar sprays on copper deficiency of wheat (Triticum aestivum) in Queensland. AUSTRAILIAN JOURNAL OF EXPERIMENTAL AGRICULTURE AND ANIMAL HUSBANDRY. 20:717-723

HARDACRE, A.K., NICHOLSON,H.F. and BOYCE, M.L.P. (1984) A portable photometer for the measurement of chlorophyll in intact leaves. NEW ZEALAND JOURNAL OF EXPERIMENTAL AGRICULTURE. 12:357-362

HOAD, G,V, and PEEL, A.J. (1965) Studies on the movement of solutes between the sieve tubes and surrounding tissues on willow;

II Pathways of ion transport from xylem to phoem. JOURNAL OF EXPERIMENTAL BOTANY 16:742-758

HOCKING,P.J., and STEER,B.T., (1983) Uptake and Partitioning of Selected mineral elements in sunflower (Helianthus annuus L.) during growth. FIELD CROPS RESEARCH 6:93-107

HULL, H.M. (1970) Leaf structure as related to absorption of pesticides and other compounds. RESIDUE REVIEWS V31

HULL H.M., MORTON, H.L. WHARRIE, J.R. (1975) Environmental influences on cuticle development and resultant foliar penetration. BOTANICAL REVIEW. 41:421-452

INNIS, W.B., WILLIAMSON, R.E. and DORSCHNER, K.P. (1951) Studies on spray retention by leaves of defferent plants. WEEDS 1:274-286

JOHNSON, D.S. (1980) Influence of phosphorus sprays on the storage quality of apples. pp327-328 In: MINERAL NUTRITION OF FRUIT TREES. ed D. Atkinson, J.E. Jackson, R.O. Sharples and W.M. Waller. Butterworths.

JONES, J.B. and ISAAC, R.A. (1972) Determination of sulphur in plant material using a Leco sulphur analyzer. AGRICULTURAL AND FOOD CHEMISTRY 20:1292-1294

JYUNG, W.H. and WITTWER, S.H. (1964) Foliar absorption - an active uptake process. AMERICAN JOURNAL OF BOTANY 51:437-444

KANNAN, S. (1980) Mechanisms of foliar uptake of plant nutrients: Accomplishments and prospects. JOURNAL OF PLANT NUTRITION 2:717-735

KANNAN, S. (1986) Foliar absorption and transport of inorganic nutrients. CRITICAL REVIEWS IN PLANT SCIENCES 4:341-375

KARHADKAR,A.D. and KANNAN, S. (1984) Transport of foliar and root absorbed copper in bean seedlings. JOURNAL OF PLANT PHYSIOLOGY 7:1443-1452

KIANG, C.K. (1982) Studies on 'leaf-tip yellowing' of citrus caused by urea sprays in Florida. PROCEEDINGS OF THE FLORIDA STATE HORTICULTURAL SOCIETY 95:40-42

KOONTZ, H., and BIDDULPH, O. (1957) Factors affecting absorption and translocation of foliar applied phosphorus. PLANT PHYSIOLOGY 32:463-470

KRAMER, P.J. (1949) PLANT AND SOIL RELATIONSHIPS M^{c}graw-Hill

LAUCHLI, A. (1972) Translocation of inorganic solutes. ANNUAL REVIEW OF PLANT PHYSIOLOGY 23:197-218

LAUER, D.A. (1982) Foliar fertilization of dry beans with Zn and NPKS AGRONOMY JOURNAL 74:339-344

LEVI, E., (1968) The distribution of mineral elements following leaf and root uptake. PHYSIOLOGIA PLANTARUM 21:213-226

LINDSAY,W.L. (1972) Zinc in soils and plant nutrition ADVANCES IN AGRONOMY 24:147-186

LLUCH, C., CAMPOS, J.A., LIGERO, F. (1983) Effect of nitrogen and sulphur fertilizers and seed inoculation with Rhizobium phaseoli on the nitrogen-sulphur relationships of bean (Phaseolus vulgaris L.) JOURNAL OF PLANT NUTRITION 6:1033-1042

LONERAGAN, J.F. and GLADSTONE, J.F., (1967) Mineral elements in temperate crop and pasture plants. AUSTRALIAN JOURNAL OF AGRICULTURAL RESEARCH

LONERAGAN, J.F., SNOWBALL,K., ROBSON,A.D., (1976) Remobilization of nutrients: Its significance in plant nutrition. pp463-469 In: TRANSPORT AND TRANSFER PROCESSES IN PLANTS. ed. I.F. Wardlaw, J.B. Passioura. Academic Press

LUCAS, R.E and KNEZEK, B.D. (1972), Climatic and soil conditions promoting micronutrient deficiencies in plants. pp 265-288 In; MICRONUTRIENTS IN AGRICULTURE ed. P.M. Giordano, W.L. Lindsay. Soil Science Society of America Inc.

LUTTGE, U. and HIGINBOTHAM, N. (1979) TRANSPORT IN PLANTS Springer-verlag

MAGALHAES, J.R. and WILCOX, G.E. (1983) Tomato growth, nitrogen fraction and mineral composition in response to nitrate and ammonium foliar sprays. JOURNAL OF PLANT NUTRITION. 6:911-939

MALAKONDAIAH, N. and RAJESWARARAO, G. (1979) Effect of foliar application of phosphorus on growth and mineral composition in peanut plants (Arachis hypogaea L.) under salt stress. PLANT AND SOIL 52:41-48

MALAKONDAIAH, N. and RAJESWARARAO, G. (1980) Effect of phosphorus on chlorophyll content, hill reaction, photophosphorylation and $^{14}CO_2$ fixation under salt stress in peanut plants. PHOTOSYNTHETICA 14:17-21

MARSCHNER, H. (1983) General introduction to the mineral nutrition of plants. pp5-60 In; ENCYCLOPEDIA OF PLANT PHYSIOLOGY. NEW SERIES V15A: INORGANIC PLANT NUTRITION ed. A. Lauchli, R.L. Bieleski Springer-Verlag

MARTIN, J.T., and JUNIPER, B.E., (1970) THE CUTICLES OF PLANTS. Edward Arnold (Publishers) Ltd.

McNEIL, D.L. (1980) The role of the stem in phloem loading of minerals in Lupinus albus L. cvr Ultra. ANNALS OF BOTANY 45:329-338

MEDERSKI, H.J. and HOFF, D.J. (1958) Factors affecting absorption of foliar applied manganese by soybean plants. AGRONOMY JOURNAL 52:175-178

MELTON, J.R., ELLIS, B.G., DOLL, E.C. (1970) Zinc, phosphorus and lime interactions with yield and zinc uptake by Phaseolus vulgaris. SOIL SCIENCE SOCIETY OF AMERICA PROCEEDINGS. 34:91-93

MENGEL, K. and KIRKBY, E.A. (1978) PRINCIPLES OF PLANT NUTRITION 3rd ed International Potash Institute.

MERRALL, G.T., (1981) Physical factors that influence the behaviour of chemicals on leaf surfaces. pp265-281 In; MICROBIAL ECOLOGY OF THE PHYLLOPLANE. ed J.P. Blakeman. Academic Press

MESDAG, J. and BALKEMA-BOOMSTRA, A.G. (1984) VarietaL differences for reaction to high acidity and to trace elements; a survey of research in The Netherlands. FERTILIZER RESEARCH 5:213-233

MIDDLETON, L.J., and SANDERSON, J. (1965) The uptake of inorganic ions by plant leaves. JOURNAL OF EXPERIMENTAL BOTANY 16:197-215

MIDDLETON, K.R. and TOXOPEUS, M.R.J. (1973) Diagnosis and measurement of multiple soil deficiencies by a subtractive technique. PLANT AND SOIL 38:219-226

MOORE, D.P (1972) Mechanism of micronutrient uptake by plants pp 171-198 In; MICRONUTRIENTS IN AGRICULTURE ed. P.M. Giordano, W.L. Lindsay. Soil Science Society of America Inc.

MOORE, D.P. (1974) Physiological effects of pH on roots. pp 135-151 In: THE PLANT ROOT AND ITS' ENVIRONMENT ed. E.W. Carson. University Press of Virginia.

MORTVEDT, J.J. and CUNNINGHAM, H.G. (1971) Production, marketing and use of other secondary and micronutrient fertilizers. pp 413-454 In: FERTILZER TECHNOLGY AND USE ed. R.A. Olsen, T.J. Army, J.J. Hanway and V.J. Kilmer. Soil Science Society of America Inc.

MULLINS, C.A. and COFFEY, D.L. (1985) Effects of molybdenum, granular inoculants and nitrogen fertilization on snap bean production and leaf nutrient content. HORTICULTURAL ABSTRACTS V55:7719

MURPHY, L.S. and WALSH, L.M. (1972) Correction of micronutrient deficiencies with fertilizers. pp 347-388 In; MICRONUTRIENTS IN AGRICULTURE ed. P.M. Giordano, W.L. Lindsay. Soil Science Society of America Inc.

NEUMANN, P.M. and PRINZ, R. (1975) The reduction by surfactants of leaf burn resulting from foliar sprays and a salt-induced inhibition of the effect. JOURNAL OF THE SCIENCE OF FOOD

AND AGRICULTURE 26:909-914

NYE, P.H. and TINKER, P.B. (1977) SOLUTE MOVEMENT IN THE SOIL-ROOT SYSTEM Blackwell scientific publications.

OKUDA, A., KAWASAKI, T., YAMADA, Y. (1960) Foliar absorption od nutrients I. The effect of different phosphorus compunds and pH on foliar absorption by use of radioactive isotopes. SOIL AND PLANT FOOD 6:66-70

OLAND, K. (1963) Responses of cropping apple trees to post-harvest urea sprays. NATURE 198:1282-1283

OLIVER, W.F. (1952) Absorption and translocation of phosphorus by foliage SCIENTIFIC AGRICULTURE 32:427-432

OLSEN,S.R. (1972) Micronutrient interactions pp243-264 In; MICRONUTRIENTS IN AGRICULTURE ed. P.M. Giordano, W.L. Lindsay. Soil Science Society of America Inc.

ORPHANOS, P.I. (1982) Spray and soil applications of zinc to apples. JOURNAL OF HORTICULTURAL SCIENCE 57:259-266

OZANNE. P.G. and PETCH, A. (1978) The application of nutrients by foliar sprays to increase yields. pp361-366 In; PLANT NUTRITION 1978. PROCEEDINGS OF THE 8th INTERNATIONAL COLLOQUIUM ON PLANT ANALYSIS AND FERTILIZER PROBLEMS. ed. A.R. Ferguson, R.L. Bieleski, and I.B. Ferguson.

D.S.I.R. Infomation Series No 134 Wellington Government Printer.

PARKER, M.B. and BOSWELL, F.C. (1980) Foliage injury, nutrient uptake and yield of soybeans as influenced by foliar fertilization. AGRONOMY JOURNAL 72:110-113

PATE, J.S. (1976) Exchange of solutes between phlem and xylem and circulation in the whole plant. pp451-473 In: ENCYCLOPEDIA OF PLANT PHYSIOLOGY NEW SERIES. V1: PHLOEM TRANSPORT. ed. M.Zimmerman, J.A. Milburn Springer-Verlag

PATE, J.S. (1980) Transport and partitioning of nitrogenous solutes. ANNUAL REVIEW OF PLANT PHYSIOLOGY. 31:313-340

PATE, J.S. and HOCKING, P.J. (1978) Phloem and xylem transport on the supply of minerals to a developing legume (Lupinus albus L.) fruit. ANNALS OF BOTANY 42:911-921

PATTERSON, M.S. and GREENE, R.C. (1965) Measurement of low energy beta-emitters in aqueous solution by liquid scintillation counting of emulsions. ANALYTICAL CHEMISTRY 37:854-857

PAULSEN, G.M. (1985) Technology for improvement and production of wheat in China. JOURNAL OF AGRONOMIC EDUCATION 14:63-68

POOLE, W.D., RANDALL, G.W. and HAM, G.E. (1983) foliar fertilization of soybeans. I. Effect of fertilizer sources, rates and frequency of application. AGRONOMY JOURNAL 75:195-200

POWLES, S.B. (1984) Photoinhibition of photosynthesis induced by visable light. ANNUAL REVIEW OF PLANT PHYSIOLOGY 35:15-44

PRASAD, M. and BRERETON, A.J.,(1970) A comparason of the effects of foliar applied and soil applied phosphatic fertilizers on crop yields. IRISH JOURNAL OF AGRICULTURAL RESEARCH 9:401-414

PRICE, C.E. (1982) A review of the factors influencing the penetration of pesticides through plant leaves. pp237-252 In; THE PLANT CUTICLE eds. Cutler, Alvin and Price. Academic Press

RALPH, W. (1982) Foliar applications of fertilizer for wheat. RURAL RESEARCH 115:24-25

REED, D.W. and TUKEY, H.B. (1982a) Light intensity and temperature effects on epicuticular wax morphology and internal cuticle ultrastructure of carnation and brussels sprouts leaf cuticles JOURNAL OF THE AMERICAN SOCIETY OF HORTICULTURAL SCIENCE 107:417-420

REED, D.W. and TUKEY, H.B. (1982b) Permiability of brussels sprouts and carnation cuticles from leaves developed in different temperatures and light intensities THE PLANT CUTICLE eds.

Cutler, Alvin and Price. Academic Press

RICEMAN,D.S., and JONES,G.B., (1958) Distribution of zinc and copper in subterranean clover (Trifolium subterraneum L.) grown in culture solutions supplied with graduated amounts of zinc. AUSTRALIAN JOURNAL OF AGRICULTURAL RESEARCH 9:73-122

RODNEY, D.R. (1952) The entrance of nitrogen compunds through the epidermis of apple leaves. PROCEEDINGS OF THE AMERICAN SOCIETY OF HORTICULTURAL SCIENCE. 59:99-102

ROMHELD, V. and MARSCHNER, H. (1979) Fine regulation of iron uptake by the Fe-efficient plant Helianthus annuus pp 405-417 In: THE SOIL-ROOT INTERFACE ed. J.L. Harley and R.S. Russell. Academic Press.

RUSSELL, E.W. (1973) SOIL CONDITIONS AND PLANT GROWTH. 10th ed. Longman Group Ltd.

RUSSELL, R.S.(1977) PLANT ROOT SYSTWMS; THEIR FUNCTION AND INTERACTION WITH THE SOIL. McGraw-Hill Book Co (U.K.) Ltd

SATO, K. (1971) Increasing the effiency of soil phosphorus fertilizer by foliar sprays of phosphorus pp 385-393 In: RECENT ADVANCES IN PLANT NUTRITION Vol2 ed R.M. SAMISH ET AL

SCHONHERR, J. (1976) Water permiability of isolated cuticular membranes; the effect of pH and cations on diffusion, hydrodynamic permiability and size of polar pores in the cutin matrix. PLANTA 128:113-126

SCHUMACHER, R., FANKHAUSER, F. and STADLER, W. (1980) Influence of shoot growth , average fruit weight and daminozide on bitter pit pp 83-91 In: MINERAL NUTRITION OF FRUIT TREES. ed D. Atkinson, J.E. Jackson, R.O. Sharples and W.M. Waller. Butterworths.

SESAY, A. (1978) physiological responses of soybeans to foliar nutrient application. DISSERTATION ABSTACTS INT. B 39:3633

SHARPLES, R.O. (1980) The influence of orchard nutrition on the storage quality of apples and pears grown in the United Kingdom. pp 17-28 In: MINERAL NUTRITION OF FRUIT TREES. ed D. Atkinson, J.E. Jackson, R.O. Sharples and W.M. Waller. Butterworths.

SHAW, B.T. (1952) SOIL PHYSICAL CONDITIONS AND PLANT GROWTH Academic Press

SHAWA,A.Y. (1982a) Response of 'McFarlin" cranberry to nitrogen sprays HORTICULTURAL SCIENCE 17:949-950

SHAWA,A.Y. (1982b) Prolonging the life of harvested 'McFarlin' cranberries. JOURNAL OF THE AMERICAN SOCIETY OF

HORTICULTURAL SCIENCE 98:212-214

SHERCHAND, K. and PAULSEN, G.M. (1985) Response of wheat to foliar phosphorus treatments under field and high temperature regimes JOURNAL OF PLANT NUTRITION 8:1171-1181

SHIM, K.K., TITUS, J.S., and SPLITTSTOESSER, W.E. (1972) The utilization of post-harvest urea sprays by senescing apple leaves. JOURNAL OF THE AMERICAN SOCIETY OF HORTICULTURAL SCIENCE. 97:592-596

SHORROCKS, V.V. and NICHOLSON, D.D. (1980) The influence of boron deficiency on fruit quality pp 103-108 In: MINERAL NUTRITION OF FRUIT TREES. ed D. Atkinson, J.E. Jackson, R.O. Sharples and W.M. Waller. Butterworths.

SILBERSTEIN. O. AND WITTWER, S.H. (1951) Foliar application of phosphatic nutrients to vegetable crops PROCEEDINGS OF THE AMERICAN SOCIETY OF HORTICULTURAL SCIENCE. 58:179-198

STEWART, I., LEONARD, C.D., EDWARDS, C. (1955) Factors influencing the absorption of zinc by citrus. FLORIDA STATE HORTICULTURAL SOCIETY 68:82-88

SUTCLIFFE, J.F. (1976) Regulation in the whole plant. pp394-317 In: ENCYCLOPEDIA OF PLANT PHYSIOLOGY, NEW SERIES V2 eds U. Luttge, M.G. Pitman Springer-Verlag

SWIETLIK, D. and FAUST, M. (1985) Foliar nutrition of fruit crops. HORTICULTURAL REVIEWS 7:287-355

SWIETLIK, D., FAUST, M. and KORCAK, R.F. (1982a) Effect of mineral sprays on photosynthesis and stomatal opening of water-stressed and unstressed applie seedlings I. Complete nutrient sprays. JOURNAL OF THE SOCIETY OF HORTICULTURAL SCIENCE 107:563-567

SWIETLIK, D., KORCAK, R.F. and FAUST, M. (1982b) Effect of mineral sprays on photosynthesis and stomatal opening of water-stressed and unstressed applie seedlings II. Potassium sulphate sprays. JOURNAL OF THE SOCIETY OF HORTICULTURAL SCIENCE 107:568-572

TABATABAI, M.A. and BREMNER, J.M. (1970) An alkaline oxidation method for determination of total sulpher in soils. SOIL SCIENCE SOCIETY OF AMERICA, PROCEEDINGS. 34:62-65

TAYO, T.O. (1981) Studies on the effects of foliar sprays of nutrients on the performance of cow peas (<u>Vigna unguiculata</u> L Walp.) JOURNAL OF AGRICULTURAL SCIENCE

TERBLANCHE,J.H., GURGEN, K.H. and HESEBECK, I. (1980) An integrated approach to orchard nutrition and bitter pit control pp 71-82 In: MINERAL NUTRITION OF FRUIT TREES. ed D. Atkinson, J.E. Jackson, R.O. Sharples and W.M. Waller. Butterworths.

THORNE, G.N. (1955) Interactions of nitrogen, phosphorus and potassium supplied in leaf sprays or in fertilizer added to the soil. JOURNAL OF EXPERIMENTAL BOTANY 6:20-42

THORNE, G.N. (1957) The effect of applying a nutrient in leaf sprays on the absorption of the same nutrient by the roots. JOURNAL OF EXPERIMENTAL BOTANY 8:401-412

THORNE, G.N. (1958) Factors affecting uptake of radioactive phosphorus by leaves and its translocation to other parts of the plant. ANNALS OF BOTANY 22:381-398

TIFFIN, L.O. (1972) Translocation of micronutrients in plants. pp 199-230 In; MICRONUTRIENTS IN AGRICULTURE ed. P.M. Giordano, W.L. Lindsay. Soil Science Society of America Inc.

TRESHOW, M. (1970) ENVIRONMENT AND PLANT RESPONSE. M^{c}Graw-Hill.

TWINE, J.R. and WILLIAMS, C.H. (1971) The determination of phosphate in Kjeldahldigests of plant material by automatic analysis. COMMUNICATIONS IN SOIL SCIENCE AND PLANT ANALYSIS 2:485-489

VAN DER BOON, J. (1980) Dressing or spraying calcium for bitter pit control. pp 309-315 In: MINERAL NUTRITION OF FRUIT TREES. ed D. Atkinson, J.E. Jackson, R.O. Sharples and W.M. Waller. Butterworths.

VASILAS, B.L., LEGG, J.O. and WOLF, D.C. (1980) Foliar fertilization of soybeans: Absorption and translocation of ^{15}N-labelled urea. AGRONOMY JOURNAL 72:271-275

VIETS,F.G., BROAWN,L.C., CRAWFORD,C.L., (1954) Zinc contents and deficiency symptoms of 26 crops on a zinc deficient soil. SOIL SCIENCE 78:305-316

VIRGIN, H.I. (1965) Chlorophyll dformation and water deficit PHYSIOLOGA PLANTARUM 18:994-1000

WALLIHAN, E.F., and HEYMANN-HERSCHBERG L., (1956) Some factors affecting absorption and translocation of zinc in citrus plants. PLANT PHYSIOLOGY 31:249-299

WEAVER, M.L., TIMM, H., NG, H., BURKE, D.W., SILBERNAGEL, M.J. and FOSTER, K. (1985) Pod retention and seed yield of beans in response applications. HORTSCIENCE 20:429-431

WELCH (1977) Foliar fertilization ILLINOIS FERTILIZER CONFERENCE.

WILLIAMS, R.F.(1948) The effects of phosphorus supply on the rates of intake of phosphorus and nitrogen and upon certain aspects of phosphorus metabolism in gramineous plants. AUSTRALIAN JOURNAL OF SCIENTIFIC RESEARCH: B 1:333-361

WITTWER, S.H. and TEUBNER, F.G. (1959) Foliar absorption of mineral nutrients. ANNUAL REVIEWS OF PLANT PHYSIOLOGY. 10:13-32

WITTWER, S.H., TEUBNER, F.G., McCALL, W.W., (1957) Comparative absorption and utilization by beans and tomatoes of phosphorus applied to the soil and foliage. PROCEEDINGS OF THE AMERICAN SOCIETY OF HORTICULTURAL SCIENCE 69:302-308

WITTWER, S.H., TEUBNER, F.G., TUKEY, H.B. (1963) Advances in foliar feeding of plant nutrients. pp 429-455 In: FERTILIZER TECHNOLOGY AND USAGE ED. Soil Science Society of America.

WITTY, J.F., ROUGHLEY, R.J., DAY,J.M. (1980) Reduction of yield of Vicia faba by foliar fertilization during the seed-filling period. JOURNAL OF AGRICULTURAL SCIENCE 94:741-743

YOGARATNAM, N. and SHARPLES, R.O., (1982) Supplementing the nutrition of bramley's Seedling apple with phosphorus sprays II. Effects on fruit composition and storage quality. JOURNAL OF HORICULTURAL SCIENCE 57:53-59

YOGARATNAM, N. and GREENHAM, D.P.W. (1982) The application of foliar sprays containing nitrogen, magnesium, zinc and boron to apple trees. I. Effects on fruit set and cropping. JOURNAL OF HORICULTURAL SCIENCE 57:151-158