PREDICTING NITROGEN REQUIREMENTS FOR ARABLE FARMING: A CRITICAL REVIEW AND APPRAISAL

K.M. Goh
Department of Soil Science, Lincoln College, Canterbury

ABSTRACT

Although nitrogen as a nutrient is widely recognised as one of the major determinants of crop yield in the field, a reliable method for predicting nitrogen requirements of crops has not been found in most cropping soils in spite of recent extensive research efforts. The main obstacles appear to be the complex behaviour of nitrogen in soils and the general lack of success of predictive methods based on laboratory, glasshouse and limited field experiments.

This paper critically reviews some of the recent research on the topic. It suggests a rationale for predicting optimum nitrogen requirements of crops based on relating crop nitrogen responses to the supply and efficiency of crop recovery of nitrogen from different sources in the soil (i.e. fertiliser + residual + mineralized nitrogen). A simple practical model incorporating the above parameters is to be established. As a long-term objective, the model can be improved by linking quantitatively to other soil, plant, management, and environmental factors which affect crop yield.

Additional Keywords: assessments, rationale, soil supplying power, crop recovery

INTRODUCTION

The importance of nitrogen as a plant nutrient in crop production systems has long been recognized. Earliest civilization adopted various soil management practices to improve crop yields. These included crop rotation, fallowing, use of manures, organic wastes and legumes. All these practices are now known to enhance the amount and availability of nitrogen to crops.

However, it is only in the last few decades that quantitative measurements of nitrogen cycle processes have been made. It is now generally accepted that nitrogen is the key to crop productivity in most instances and it produces the greatest impact in crop production compared with all the nutrients supplied to crops (Cooke, 1979; Kirkby, 1981).

Several recent studies (e.g. Stephen, 1980, 1982; Tinker and Widdowson, 1982) have indicated that crop yields can only be maximised through careful control of the use of nitrogen fertilisers. For example, Stephen (1980) cited 222 field experiments on wheat in northern Canterbury which showed that 21% of all trial sites showed an economic return to the application of 75 kg N/ha while 79% either depressed grain yield or produced no positive effect. These data indicate that nitrogen usage on crops needs to be rigidly controlled and a predictive method for crop nitrogen requirements is essential. The control is needed not only to ensure high economic returns to the farmer but also to avoid environmental pollution of groundwater with nitrate (Kolenbrander, 1973; Verstraete, 1981; Goh, 1982a). The aim of fertiliser use is to supply an adequate but not excessive amount of nitrogen to the crop. Such an objective can only be achieved if the nitrogen requirements of arable crops can be accurately defined and reliably predicted.

In spite of extensive recent research efforts, a reliable method for predicting crop nitrogen requirements has not been found in most cropping soils (Stanford, 1982). Some limited successes have been obtained in a few countries (e.g. Ris *et al.*, 1981; Becker and Aufhammer, 1982). Nitrogen behaves in an extremely complex manner in soils involving a multiplicity of chemical forms and interacting processes (Gasser, 1982; Stevenson, 1982a). This complex behaviour has hindered the precise control and adjustments of nitrogen availability by farmers to meet crop requirements.

The present paper reviews recent literature on the topic and suggests a rationale for predicting optimum nitrogen requirements for arable crops.

PLANT-AVAILABLE NITROGEN IN SOILS

It is commonly accepted that plant-available nitrogen in soils is largely represented by ammonium (NH_4^+) and nitrate (NO_3^-) nitrogen present within the active root zone so as to be readily absorbed by plant roots. Nitrites (NO_2^-) and simple organic nitrogenous compounds such as free amides and free amino acids are not important sources as these forms are unstable in soils. Both ammonium and nitrate are equally available to most plants although some plants show a preference for one form or the other (Haynes and Goh, 1978).

In the soil, nitrogen is present mainly in organic forms (>90%) (Goh and Edmeades, 1979; Stevenson, 1982b). This nitrogen is made available for plant use through the process of mineralization by micro-organisms as shown in Fig. 1.

The soil available nitrogen is sometimes supplemented by nitrogen fertiliser additions.

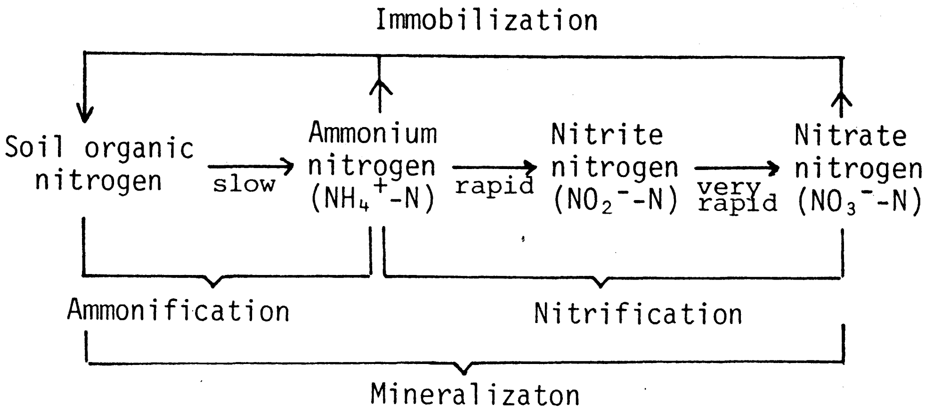

Figure 1: Flow diagram of nitrogen tranformation in soils.

Under temperate conditions only a small proportion (1-3%) of the total soil nitrogen is released each year in plant-available forms (Broadbent *et al.,* 1964; Ludecke and Tham, 1971; Campbell, 1978; Hart *et al.,* 1979). Many environmental (e.g. temperature, moisture, aeration, wetting and drying, freezing and thawing), soil (e.g. pH), cultural (e.g. cultivation) and plant factors (e.g. root exudates) affect the rate of nitrogen release. These factors have been extensively reviewed and discussed elsewhere (e.g. Bartholomew, 1965; Harmsen and Kolenbrander, 1965; Alexander, 1977; Campbell, 1978; Hart *et al.,* 1979). Stanford and Smith (1972) found that in 39 United States soils only 5 to 40% of the total soil nitrogen could be mineralized in infinite time (i.e. N_0 or the mineralization potential). This may account for the general lack of success in using the total soil organic matter or nitrogen content to predict the nitrogen-supplying power of soils.

METHODS OF ASSESSING SOIL NITROGEN AVAILABILITY

In the last 30 years, various laboratory, glasshouse and field methods have been used to assess soil nitrogen availability, but with varying success. A reliable method has yet to be found for most cropping soils. Ideally, the method should be able to predict reliably the nitrogen requirements of a crop in one or more soil types and climatic conditions so that it could be used with confidence for routine fertiliser recommendations.

Most of the methods which have been studied aim at measuring the release of plant-available nitrogen from soil organic matter. These methods have been extensively reviewed and discussed elsewhere (e.g. Harmsen and Van Schreven, 1955; Bremner, 1965; Keeney and Bremner, 1966; Robinson, 1975; Campbell, 1978; Stanford, 1982). For this reason, only the more important aspects of some methods are elaborated and discussed here.

LABORATORY INCUBATION METHODS

These methods are studied most intensively and are most widely used. They are based on the incubation of soils under controlled laboratory conditions for a short-term (1 to 6 weeks) or long-term (about 30 weeks) period. The amount of nitrogen (ammonium or nitrate or both) released is calibrated against plant responses in the glasshouse or field experiments.

Short-Term Incubation Methods

These involved incubating soils in the laboratory under constant temperatures (25°, 30° or 40°C) either aerobically for a period of 2 to 6 weeks or anaerobically for 1 week. Under anaerobic conditions only ammonium is released and this is measured, while under aerobic incubation both ammonium and nitrate nitrogen are measured.

Bremner (1965) concluded from his evaluation of more than 30 short-term incubation procedures that the methods offered great reliability and high reproducibility. However, the results were extremely sensitive to incubation conditions and methods of sampling, drying, grinding, sieving and storage of soil samples. Thus a satisfactory method can only be found if the conditions of sample preparation and incubation are rigidly standardized and controlled.

Although short-term incubation procedures attempt to simulate the action of micro-organisms in releasing plant-available forms of soil nitrogen, the incubation conditions used are markedly different from those in the field or glasshouse and the period of incubation (1 to 2 weeks) does not reflect the amount of nitrogen which is likely to be released during the life cycle of a crop. Thus only a portion of the mineralizable soil nitrogen is measured.

Long-Term Incubation Methods

Stanford and co-workers (Stanford and Smith, 1972; Stanford *et al.,* 1973; 1974; 1977) developed a method aimed at measuring the long-term nitrogen supplying power of soils. Soil samples were incubated over a 30-week period at 35 °C under optimum soil water conditions with intermittent leachings with 0.01 M $CaCl_2$ and a nutrient solution without nitrogen. The consecutive incubation intervals used varied from 2 to 8 weeks and the amount of nitrogen released was determined in each incubation over the 30-week period to give the cumulative nitrogen mineralization or N_t.

These workers hypothesized that the rate of nitrogen mineralization was proportional to the quantity of nitrogen comprising the mineralizable substrate. They proposed the term "the mineralization potential" or N_0 as the quantity of soil organic nitrogen that is susceptible to mineralization at time zero according to the first order kinetics

$$\log (N_0 - N_t) = \log N_0 - kt/2.303$$

where N_0 = mineralization potential (mg/kg)
N_t = nitrogen mineralized cumulatively in time t(weeks)
k = mineralization rate constant (weeks^{-1})

The N_0 was obtained graphically from plots of log (N_0 -N_t) vs t (Stanford and Smith, 1972) or using an iterative computer method (Campbell *et al.,* 1981). A considerably shorter total incubation time (i.e. 2 to 4 weeks) can be used to measure N_t instead of the 30-week period, provided the preliminary release of nitrogen in the first two weeks are not used in the estimation of N_0 (Stanford *et al.,* 1974).

Largely due to the less empirical nature of the N_0 approach compared with other incubation methods, several workers have attempted to adopt the N_0 method for application to field and glasshouse conditions. Relationships between N_0 and changes in soil temperature and moisture are used to adjust N_0 values (Smith *et al.,* 1977; Herlihy, 1979; Cassman and Munns, 1980; Campbell *et al.,* 1981; Farooi *et al.,* 1983). These predictive nitrogen models were found to be successful for predicting the nitrogen requirements of irrigated wheat in Chile (Oyanedal and Rodriguez, 1977; Prado and Rodriguez, 1978).

CHEMICAL EXTRACTION METHODS

Chemical indices of soil nitrogen availability are attractive to users because the extraction methods used are more rapid, precise and convenient than biological incubation techniques. Numerous extractants have been studied (Bremner, 1965; Stanford, 1982). They ranged from strong reagents (e.g. 6 N HC1) to intermediate (e.g. alkaline $KMnO_4$) and mild extractants (e.g. 0.01 M $CaCl_2$, boiling water). As expected, the amount of nitrogen extracted by each extractant varies according to the nature of the reagent and extraction conditions used (e.g. temperature, extraction time).

None of the proposed chemical indices have been put to general use. For a broad range of soils, the results do not correlate consistently with reliable biological measurements of soil nitrogen availability (e.g. mineralizable nitrogen or crop yield). As most of the chemical methods are empirical it is unlikely that a chemical reagent could be found which would simulate microbial activities in the release of soil nitrogen or selectively extract the fraction of soil organic nitrogen which is to be made available to plant uptake by soil micro-organisms.

However, Fox and Piekielek (1978) reported in a 2-year study of eight Pennsylvanian soils that the MacLean test (i.e. 0.01 M $NaHCO_3$) modified for determination as absorbance at 260 nm (Fox-Piekielek test) provided reliable predictions of nitrogen uptake by maize. Recently, Whitehead *et al.* (1981) found that, of the 5 chemical nitrogen indices studied, the best prediction of nitrogen uptake by perennial ryegrass in the field at 18 sites in the United Kingdom was given by a method which combined the measurement of "glucose" extracted by 0.05 M $Ba(OH)_2$ with the amount of nitrate nitrogen extracted by 2 M KC1 from soils sampled in the winter or early spring. The combined value was then adjusted for soil temperature and water status present at each site. The result accounted for 65% of the variation in the herbage nitrogen yield.

Whitehead (1981) compared 9 chemical extraction methods for predicting the nitrogen supply in 21 soils by relating the comparisons to nitrogen uptake by perennial ryegrass plants under glasshouse conditions. He found the best prediction was given by a method which involved boiling the soil with 1 M KC1 followed by the determination of the mineral nitrogen (i.e. NH_4^+-N + NO_3^- -N) released. This method accounted for 80% of the variation between soils in the herbage nitrogen yield. Whitehead (1981) attributed the predictive success of the method to its ability to extract simultaneously the mineral nitrogen present in the soil at the time of sampling and the mineralizable nitrogen released through mineralization during the growing phase of the ryegrass plants.

GLASSHOUSE OR POT ASSESSMENTS

Assessments of soil nitrogen availability are usually conducted in the glasshouse under controlled conditions with pot culture techniques as a first step in the calibration and comparisons of chemical and biological nitrogen indices (Keeney and Bremner, 1966; Robinson, 1975; Whitehead, 1981; Stanford, 1982). These studies normally showed that soil nitrogen uptake by plants provided a better estimate of nitrogen availability than either plant yield responses or plant yield in the zero-nitrogen pots. When successive crops are grown, the cumulative nitrogen uptake is better related to the combined function of the initial mineral nitrogen and the relative availability of the soil organic nitrogen.

Glasshouse experiments are more precise and rapid than field experiments although they are less rapid and precise than laboratory methods (Fried and Broeshart, 1967). A wider range of soils can be used in the glasshouse than in field experiments. Because of these advantages, many workers relied solely on glasshouse results for testing their nitrogen availability indices. Few workers compared glasshouse results with field-available nitrogen over a growing season. Recently, Michrina *et al.* (1981) made this comparison for 10 Pennsylvanian soils and found that the correlation was non-significant. These workers suggested that glasshouse results could not be substituted for field experiments in testing the reliability of laboratory nitrogen indices.

FIELD METHODS

Various field methods have been used to predict nitrogen requirements of crops. They range from general experience of cropping farmers to measurements of rainfall and other climatic parameters (e.g. temperature). A particular method may be used successfully in one region or country but not in others. However, in spite of the limitations of field methods as being generally less precise and more expensive and troublesome than other procedures, field methods uniquely reflect the actual soil-plant relationship in the farmer's field. For this reason, many of the recent studies of soil nitrogen availability have involved field assessments.

Previous Cropping or "Paddock" History

Stephen (1980, 1982) has reviewed earlier field experiments on wheat in New Zealand which showed that yield responses are dependent on paddock history related to the previous crop. For example, Hudson and Woodcock (1934) reported that wheat responded to applied nitrogen fertilisers most frequently when the preceding crop was cereal and least frequently when it was a pasture or a forage crop. Stephen (1982) also cited his own experimental results in South Canterbury which showed that spring applications of lime ammonium nitrate at 60 to 120 kg N/ha only increased wheat grain yields in the second and third winter-sown wheat crops but not in the first crop after pasture.

Soil nitrogen indices currently used for advisory purposes in the United Kingdom are also based on the residual effects of previous cropping (MAFF, 1967, 1979; Needham, 1982). The effects of the last crop are usually considered. Soils are ranked according to whether the previous crop or pasture promotes or depletes soil nitrogen reserves.

However, the general rule of thumb based on paddock history is highly empirical and subjective. Many instances of difficulties in using this approach have been cited by several workers (e.g. Lynch, 1959; McLeod, 1962; Douglas, 1968; Walker, 1969; Ludecke, 1974). More recently, Steele and Cooper (1980) cited research evidence which showed that some North Island soils can be cropped continuously for 11 years without showing nitrogen responses while other soils responded to nitrogen fertiliser additions in their first year out of pasture. Obviously, the previous cropping approach without quantitative soil and/or plant measurements is largely approximate and unsatisfactory.

Residual Nitrate or Mineral Nitrogen

In some countries overseas, predictions of nitrogen requirements of crops have been successfully based on measurements of soil nitrate (NO_3^--N) or mineral nitrogen (NH_4^+-N + NO_3^--N) levels in the field taken before active plant growth commences (i.e. late winter or early spring period). This method has recently received some prominence in New Zealand.

The method is employed most successfully in West Germany and forms part of the routine procedure used for predicting the amount of fertiliser nitrogen required by winter wheat (Jungk and Wehrmann, 1978; Becker and Aufhammer, 1982). It involves the determination of mineral nitrogen (N_{min} reserve) in the soil before spring growth begins, incorporating the total active root zone (i.e. 0 to 900 mm in southern Hanover loessial soils). Nitrogen fertiliser is then applied usually between late seedling growth and early tillering period to bring the total available nitrogen level (N_{min} reserve + $N_{fertiliser}$) up to 120 kg N/ha. This is followed by additional fertiliser nitrogen applications of 20-30 kg N/ha during stem elongation and of 50-60 kg N/ha at ear emergence as determined by plant anaylsis of nitrate content in the xylem sap of stems. A similar technique is also used in the Netherlands for arable crops (e.g. winter wheat, potatoes, sugar beet) (Ris *et al.*, 1981).

Several workers in the United States and Canada found significant correlations between residual soil nitrate levels and nitrogen uptake by crops and used these as a basis for nitrogen fertiliser recommendations (e.g. Leggett, 1959; Soper and Huang, 1963; James *et al.*, 1967; Soper *et al.*, 1971; Dahnke and Vasey, 1973; James, 1978). For example, Soper *et al.* (1971) found in 22 field trials in Canada over a 7-year period, the best correlation (r^2 = 0.84) was obtained when the residual soil nitrate level present to a depth of 610 mm was taken into account.

Ludecke (1974) demonstrated a significant relationship between soil nitrate nitrogen levels at 0-900 mm depth in the soil at late winter - early spring period (August-September) and grain yield response of autumn-sown wheat to nitrogen fertiliser in Canterbury. This relationship has been used as the "deep nitrate" test in which the soil is sampled to 0-600 mm depth by a Canterbury/Southland fertiliser company as a service to crop farmers and also by other workers (e.g. Stephen, 1980). The test assumes that no fertiliser nitrogen is required when the soil nitrate nitrogen level at 0-600 mm depth in August-September exceeds 12 ppm. Below this nitrate nitrogen level, nitrogen requirement of autumn-sown wheat increases linearly with the decrease in soil nitrate nitrogen with a maximum requirement of 85 kg N/ha. Recently, Walker and Ludecke (1982) showed that the best linear relationship (r^2 = 0.82) is given by the equation: $y = 1967 - 18.5\,x$

where y = wheat grain response or depression in kg/ha due to lime ammonium nitrate addition at 85 kg N/ha

x = nitrate nitrogen in kg/ha in the soil to a depth of 0-900 mm in August.

Although the "deep nitrate" method is a distinct improvement over the "previous cropping history" approach, it is not without difficulties (Quin, 1982; Quin *et al.*, 1982). Nitrate levels in the soil are affected by heavy rain before and after sampling in the winter-early spring period because of leaching losses. These levels change with time (Hart *et al.*, 1979) and it is therefore difficult to define exactly the most appropriate time to sample the soil for nitrate. Furthermore, the amount of mineral nitrogen released in the soil during the growing season is not incorporated in the test. For example, Hart *et al.* (1979) found from continuous field measurements that more than

200-300 kg N/ha was released in the soil in Canterbury at 0-800 mm depth during the whole growing season of a wheat crop (i.e. 9 months). The mineralized nitrogen in the cropped and fallow soils was calculated to represent more than 2 to 4 times that measured by the "deep nitrate" test (Quin and Drewitt, 1979).

Recently, Needham (1982) reported that the residual mineral nitrogen method of Scharpf and Wehrmann (see Jungk and Wehrmann, 1978) was tested in the United Kingdom without much success. It was suggested that the wider range of soils and climatic conditions in the United Kingdom compared with those in West Germany were the main factors responsible for the poor relationship observed. It is therefore apparent that the "deep nitrate" test method on its own is of limited value in predicting the nitrogen requirements of crops across a range of soil and climatic conditions.

Residual and Mineralizable Soil Nitrogen

As pointed out earlier, a considerable portion of the nitrogen taken up by crops is derived from the nitrogen released from the mineralization of soil organic nitrogen reserves. Only a few studies in New Zealand have actually attempted to measure directly in the field the total amount of the nitrogen mineralized in the soil during crop growth.

In the United States, Geist and co-workers (Reuss and Geist, 1970; Geist *et al.*, 1970) were among the first to attempt to use both available soil mineral nitrogen and nitrogen released from soil organic matter for predicting crop yield responses or nitrogen uptake. They used a polynomial equation of:

$$Y = B_0 + B_1 (X_1 + aX_2) + B_2 (X_1 + aX_2)^2$$

where

B_0, B_1, B_2 = regression coefficients
Y = yield or other parameter
X_1 = fertiliser + residual mineral nitrogen
X_2 = an index of soil organic nitrogen availability
a = estimated fraction of X_2 released.

Stanford (1973) presented a more direct approach in estimating the nitrogen needs of the crop as:

$$N_c = N_i + N_m + N_f$$

where

N_c = nitrogen uptake by a crop associated with a specified maximum or attainable economic yield.
N_i = measured initial quantity of nitrogen in the soil profile.
N_m = estimated nitrogen mineralized during the cropping season.
N_f = amount of nitrogen fertiliser needed.

Carter *et al.* (1974, 1975) estimated the nitrogen fertiliser requirement of sugar beet by using empirical utilization coefficients for N_i and N_f calculated from earlier field experimental data. Stanford *et al.* (1977) estimated N_c for a sugar beet crop using the nitrogen potential, N_0, which was adjusted to account for the varying temperatures and soil water regimes in the field by laboratory - established empirical equations. The same approach has been applied successfully to wheat crops in Chile as pointed out earlier (see Oyanedel and Rodriguez, 1977; Prado and Rodriguez, 1978).

More recently, Quin *et al.* (1982) proposed a soil "incubation test" method for predicting the yield of wheat in Canterbury. Fresh, moist soil samples (0-150 mm depth) were incubated in the laboratory at 37 °C to estimate the change in mineral nitrogen level (i.e. ΔN) as the difference in mineral nitrogen before and after incubation. A combination of twice in the ΔN and the initial mineral nitrogen (IN) is used to predict wheat yield on zero-nitrogen plots using the equation:

$$Y_0 = 1 + 0.0417 (IN + \Delta N)$$

where

Y_0 = expected yield without nitrogen fertiliser or zero-N (t/ha)
IN = nitrogen concentration before incubation or initial nitrogen (ppm)
ΔN = change in nitrogen concentration between the initial nitrogen and final nitrogen after 7 days incubation at 37 °C (ppm).

The amount of nitrogen fertiliser required to maximise yield is calculated from the predicted yield equation of zero-nitrogen plots (Y_0), the known potential yield for the area (Y_p) and the efficiency of conversion of nitrogen to grain by the following equation:

$$\text{Nitrogen to apply (kg/ha)} = (Y_p - Y_0) \times 40$$

where

Y_p = estimated yield potential (t/ha)
Y_0 = expected yield without nitrogen fertiliser (t/ha)
40 = amount of nitrogen required per tonne of grain responses for Canterbury (or 50 for Otago-Southland).

The test was developed using soil samples collected in late winter-early spring. The authors proposed that the method can be used in autumn after correction for winter leaching or throughout spring after correction for nitrogen already present in the crop. They also stated that the test is equally suitable for autumn, winter and spring-sown wheat and may be used for barley and oats with little or no modification. However, the authors did not present experimental data in support of their recommendations for the proposed wide ranging uses of their test.

Mineralizable Soil Nitrogen

Steele *et al.* (1982a) found that the residual mineral nitrogen content in the moist soils (0-600 mm depth) collected in October under maize cropping trials in the North Island of New Zealand showed a poor relationship to the yield of control maize crops without added fertiliser nitrogen. However, the mineral nitrogen released from the soil samples after being dried for 15 h in a forced air oven at 33 °C showed a significant relationship to maize yield in control or zero-nitrogen plots. For example, the relationship for the Waikato region is given by:

$$Y = 1.13 + 0.122X - 0.000418X^2$$

where

Y = maize grain yield in t/ha (14% moisture) when the maize is sown with 20 kg N/ha as a starter fertiliser.

X = mineral soil nitrogen measured in the dried soil at 0-600 mm depth (kg N/ha).

A small amount of nitrogen (e.g. 20 kg N/ha) is usually applied in the seed bed as a starter fertiliser and the prediction is for the fertiliser required as a post-emergence dressing.

Steele *et al.* (1982a) commented that the forced air drying of the soil samples was acting as a short-term incubation allowing the mineralization of soil organic nitrogen. They presented evidence that maize grain yield increase per unit of nitrogen applied was independent of climate, crop management or soil type, but dependent mainly on relative yield when nitrogen was applied and on the potential yield of the site. The grain yield response to nitrogen fertiliser is estimated from the expected and potential yields. The former was obtained from the 'soil-drying' incubation test while the latter from farm and district records of past years.

Climate Parameter Approach

A few recent studies have attempted to assess the availability of soil nitrogen to crops in the field by measuring certain climatic parameters (e.g. rainfall, temperature, soil moisture). The climatic data are used quantitatively to estimate either the rate of soil nitrogen mineralization or the loss of nitrate by leaching.

Campbell *et al.* (1975) used multiple regression equations to quantify relationships of soil nitrate production and environmental conditions in the field and in simulated field conditions in the laboratory. They found that the mean daily change in topsoil (0-25 mm) nitrate concentration in the field was negatively correlated with the mean daily change in soil moisture. Wetting and drying accounted for 70-90% of the observed nitrate concentration increases. Of the increases in nitrate concentration, 88% were due to upward movement of soil moisture as a result of evaporation and only 12% due to nitrification. Changes in soil moisture were also found to be the main factor affecting nitrate concentration changes in the laboratory studies simulating field conditions. However, laboratory and field studies differed in that changes in soil moisture interacted primarily with initial moisture content in the field study but primarily with temperature in the laboratory.

Hart and Goh (1980) measured soil mineral nitrogen (NH_4^+ -N + NO_3^- -N) levels at five depths (0-800 mm) and some climatic and environmental variables in a field trial in Canterbury under fallow and a wheat crop for 9 months. Significant linear and quadratic relationships were obtained between mineral nitrogen levels or total nitrogen uptake by wheat and soil heat accumulation (temperature), soil moisture and rainfall. The maximum r^2 value (37%) was obtained for nitrate nitrogen changes in the topsoil (0-100 mm). These workers proposed that measurements of climatic variables in the field may be used to predict nitrogen requirements of crops especially when long-term weather forecast information becomes available.

Feyter *et al.* (1977) developed the "winter-rainfall" method for predicting nitrogen responses of spring-sown wheat in Southland and Otago. The test constitutes a broader application of the "deep-nitrate" soil test. It is based on the concept that the greater the winter rainfall, the more severe the loss of soil nitrate by leaching resulting in a greater likelihood of nitrogen response to fertiliser nitrogen. The relationship used:

Predicted Response (kg/ha) = 1.9 x rainfall April-June (mm) + 175.1 x rainfall intensity (mm/rain day) - 1134

The equation was used to predict yield responses to 75 kg nitrogen per ha. The test was relatively successful for second crop of spring-sown wheat on deep soils in Southland where soil nitrogen availability was largely affected by winter leaching of soil nitrate. It was not successful for third or subsequent crops of wheat probably due to increased variability of soil nitrogen status between paddocks (Feyter and Cossens, 1977). Nevertheless, the technique has the advantage of dispensing with the need to sample soils or plants.

Plant Analysis

Chemical analysis of plant parts of crops for nitrogen (e.g. sap tests for nitrate) is not generally used for predicting nitrogen requirements because of the complexity or lack of reliable quantitative relationships between plant nitrate content and soil nitrogen supply. However, plant analysis can be used successfully to complement soil tests, especially for monitoring the adequacy of nitrogen in the plant at sensitive growth stages or for providing information on the amount of nitrogen fertiliser to be applied to subsequent crops.

As discussed earlier, nitrate analysis of the xylem sap of wheat stem is used as part of a routine procedure for recommending nitrogen fertiliser application to winter-grown wheat in West Germany (see Jungk and Wehrmann, 1978). It has also been recommended for general use in New Zealand (Cornforth, 1980). More recently, Withers (1982) demonstrated a visual relationship between sap nitrate levels and the final yields of wheat and barley in some trials in Palmerston North.

Steele *et al.* (1982b) proposed the use of leaf or grain nitrogen concentration in maize crops for estimating the amount of nitrogen fertiliser to be applied to subsequent maize in a continuous cropping sequence. These workers found that maximum grain yield of maize was associated with 3.12% nitrogen in ear leaves sampled at 50% silking and 1.52% nitrogen in grain. The method is likely to be broadly qualitative as soil and growing season conditions which affect soil nitrogen availability probably differ between succeeding crops.

BASIS FOR NITROGEN FERTILISER RECOMMENDATIONS FOR CROPS IN NEW ZEALAND

As a general rule, nitrogen fertiliser recommendations for different crops in New Zealand are still largely based on local farming experience and practices. Predictive methods based on scientific principles are not used except those for wheat and maize as discussed earlier.

Cornforth and Sinclair (1982) recently compiled the main recommendations for cereals. These together with those currently used for other crops are summarized below for discussion purposes.

Wheat

Four methods are currently recommended for predicting the nitrogen requirements of wheat (Greenwood *et al.,* 1982), presented earlier. They include the:

(i) Previous cropping history or "paddock history" approach
(ii) "Deep-nitrate" soil test
(iii) "Winter-rainfall" method
(iv) "Soil incubation" method

Barley and Oats

The above methods recommended for wheat have also been recommended for barley and oats (Greenwood *et al.,* 1982), although scientific evidence for this application has not been confirmed.

Maize

The soil analysis method based on the "drying-soil" test (Steele *et al.,* 1982a) has been recommended (Steele, 1982) and it is available for routine use through private soil testing laboratories. The plant analysis method (Steele *et al.,* 1982b) has been recommended for general use (Cornforth, 1980; Steele, 1982).

Brassicas (Swedes and Kale), Potatoes, Linseed

No recommended methods have been proposed other than those based on local practices and experience.

Horticultural Crops

Horticultural production, especially vegetable production, represents an intensive form of arable farming. Larger quantities of nitrogen fertiliser (e.g. 100-400 kg N/ha) are used compared with agricultural crops to produce high-value cash crops. In spite of this, very little research has been conducted on predicting the nitrogen requirements of horticultural crops.

Many of the current nitrogen fertiliser recommendations are based on local experience and practices (Wallace, 1976; Malden, 1982), local field trials (Webster, 1969; Wilson, 1975; Minard, 1977), total removal of nutrients by the crop (Bradenburg, 1980) or extrapolated from overseas literature without local confirmation. For these reasons, recommendations are often imprecise and at variance with experimental results (Goh and Vitaykon, 1983)

DISCUSSION

It is evident from this review that a reliable method for predicting the nitrogen requirements of arable crops has not been found in most cropping soils. Some successes have been reported under carefully controlled and standardized conditions in the glasshouse and also under uniform soil and climatic conditions in the field. However, in most instances where these conditions do not exist, limited success has been obtained. For this reason, although further research on this aspect is warranted, future reseach should be objectively designed and non-repetitious of past work.

Some significant advances have been made in recent years for predicting nitrogen requirements of wheat (Quin *et al.,* 1982) and maize (Steele *et al.,* 1982a) in New Zealand. However, as both these methods are very recent, their reliability has yet to be assessed. These methods are based on short-term incubation of soils in the laboratory to predict the amount of nitrogen likely to be released in the field by the mineralization of soil organic nitrogen during crop growth. The prediction of crop yield response due to nitrogen fertiliser additions is based on the relationship between laboratory estimates of soil nitrogen mineralization and the yield of the control of zero-nitrogen plots.

As pointed out earlier, short-term incubation tests are relatively rapid and best suited for a routine soil testing service. However, the reproducibility of their results is highly dependent on rigid control and standardization of the procedure (Bremner, 1965). Furthermore, it is reasonable to conclude that because the incubation conditions in the laboratory bear little or no resemblance to those in the field and the incubation duration is relatively short (18 h or 7 days), the amount of soil nitrogen released in incubation experiments would not be quantitatively close to that released during the total growing season of a crop. This factor has not been examined by Steele *et al.* (1982a) or Quin *et al.* (1982) although Quin *et al.* (1982) considered this aspect to be one of the major limiting factors of the "deep-nitrate" method of Ludecke (1974).

The use of the control or of the zero-nitrogen plots assumes the following are valid:

(i) The control or zero-nitrogen plots can be defined reliably.
(ii) Deficiencies of nutrients other than nitrogen can be precisely determined.
(iii) Addition of nitrogen fertilisers produce no "priming effects" on the mineralization of soil organic matter.
(iv) The potential yield of a crop is determined solely by the quantity of available soil and fertiliser nitrogen present and is independent of soil type, climate and management practices.

In practice, control or zero-nitrogen plots are difficult to characterise agronomically and chemically using quick soil tests as these plots may vary in different degrees of deficiencies for nitrogen and/or other nutrients. For example, Brockman (1974) demonstrated that zero-nitrogen plots differed considerably in their ability to supply nitrogen.

Additions of nitrogen fertiliser to soils have been shown to stimulate the mineralization of soil organic matter known as the "priming effects" (e.g. Legg and Stanford, 1967; Broadbent and Nakashima, 1971; Jenkinson, 1971; Westerman and Kurtz, 1973; Westerman and Tucker, 1974; Laura, 1975). Differences in net soil nitrogen mineralization between fallow and cropped soils have also been reported (Hart *et al.,* 1979). For this reason, soil nitrogen mineralization in control or zero-nitrogen plots is unlikely to reflect that in nitrogen-treated plots. The estimation of the apparent recovery of nitrogen does not distinguish between fertiliser nitrogen and soil nitrogen. This distinction is needed to determine the amount of nitrogen fertiliser to apply to a crop.

Steele *et al.* (1982a) reported that, in the major maize growing regions of the North Island of New Zealand, the effect of nitrogen fertiliser on maize grain yield was independent of climate, soil types and crop management practices. These workers determined the expected increase in grain yield per kg of nitrogen from field experiments. However, the potential yield was obtained from district and farm records. A similar approach was used by Quin *et al.* (1982), employing different conversion factors for Canterbury and Southland-Otago to estimate the amount of nitrogen fertiliser required to achieve maximum wheat yield. Furthermore, the linear relationship between wheat grain yield and soil available nitrogen (i.e. $Y_0 = 1.0 + 0.0417 (IN + \Delta N)$ in the zero-nitrogen plots as established by Quin *et al.* (1982) shows that wheat yield continues to increase from 2 t/ha to over 10 t/ha without showing any decreases in yield at the very high nitrogen levels. This implies that excess nitrogen does not depress yield which is contrary to current findings (e.g. Stephen, 1980).

The basic assumption underlying these calculations is that the potential or maximum yield of a crop as obtained from past farm records is determined solely by the quantity of available soil and fertiliser nitrogen present and is independent of soil, climate and management factors. This is contrary to the recent finding of Tinker and co-workers (Tinker, 1979; Tinker and Widdowson, 1982) which shows that no single factor could be identified to explain why maximum wheat yield was obtained or varied between sites. Benzian and Lane (1982) demonstrated that the nitrogen (protein) concentration of wheat grain is influenced by several husbandry factors. Stephen (1982) cited that one of the highest grain yields of wheat recorded in New Zealand (10,620 kg/ha) was obtained without the use of nitrogen fertiliser.

Precise quantitative measurements in the field of crop recovery of nitrogen fertilisers and soil nitrogen released from the mineralization of soil organic matter have not been conducted extensively in New Zealand. Several recent studies in New Zealand and overseas have shown that the distribution of nitrogen within a wheat crop is extremely sensitive to environmental and management factors (e.g. Evans *et al.,* 1975; Scott *et al.,* 1977; Langer, 1980; Scott, 1981; Benzian and Lane, 1982; Olson and Kurtz, 1982).

Cooke (1979) emphasized the necessity for continued research on the uptake of nitrogen by crops and the relationships between nitrogen uptake and crop yields Gregory *et al.,* (1981) stated that a knowledge of how nitrogen status of a crop affects photosynthesis is central to an understanding of nitrogen and crop yield relationships. Thus, several factors interact and the prediction of nitrogen requirements of crops would have to take into account the physiological aspects of crop nitrogen nutrition and the effects of soils, environment, and management practices.

In Canterbury, nitrogen responses of wheat have been shown to be highly dependent on the availability of soil moisture (e.g. Drewitt and Rickard, 1973; Dougherty *et al.,* 1975; Scott, 1977; Drewitt, 1979). The method of Quin *et al.* (1982) was established on soils without moisture stress. Thus, it should not be used indiscriminantely on non-irrigated wheat.

RESEARCH PERSPECTIVES AND PRIORITES

Current practical advice on nitrogen requirements of crops relies largely on empirical interpretations of laboratory and field trials. Although empirical methods are useful for practical reasons, their reliability is often short-term and decreases with the time of usage when the methods are extended to a wider range of soil-plant and climatic conditions than those used in the establishment of the methods. This is revealed when one traces the history of the development of empirical soil test methods. Empirical methods require extrapolation of results with assumptions to unknown situations. Laboratory methods of estimating the nitrogen supplying power of soils provide relative rather than the actual amounts of soil nitrogen made available to the crop in the field. For a meaningful prediction of crop nitrogen requirements, it is essential that the laboratory estimation of the mineralizable soil nitrogen should not only be well correlated with crop yield but also quantitatively close to that released in the field during crop growth.

The likelihood of predicting successfully crop nitrogen requirements is ensured when sound principles of soil science and plant nutrition are used in the development of soil test methods as in the system approach (see Greenwood *et al.,* 1974; Stanford *et al.,* 1977; Campbell *et al.,* 1981; Greenwood, 1982; Tanji, 1982).

As stated previously, many interacting processes in the soil and the crop affect crop nitrogen responses. A rational approach to predicting nitrogen requirements of crops is needed. This should attempt to measure quantitatively some of the important processes in the field and integrate them into a practical model for general use. A simple model should first be developed for a single crop in a limited range of soils and climatic conditions. This model could be based on relating quantitative field measurements of the major categories of plant-available nitrogen in the soil (i.e. residual nitrogen + mineralized nitrogen + fertiliser) to crop nitrogen uptake and yield. The model could then be improved later by linking quantitatively to a larger number of soil, plant, climate and management factors as a long-term objective.

The basis for effective prediction of crop nitrogen requirements should ideally rely on information related to:

(i) The nitrogen suppyling power of the soil.
(ii) Individual crop demands for nitrogen.

The ability of a soil to supply nitrogen to a crop is a measure of the amount of nitrogen made available to the crop during the growing season in the field. This is determined by:

(i) The amount of available soil nitrogen (NH_4^+ -N + NO_3^- -N) present in the active root zone early in the season before crop growth commences (i.e. residual nitrogen).
(ii) The capacity of the soil for mineralization and release of nitrogen from soil organic matter during the cropping season.
(iii) The availability of nitrogen fertiliser when added to supplement soil nitrogen supply.

(iv) The efficiency of a crop to recover these available nitrogen sources.

All these factors were rationalised by Stanford (1973) in the equation:

$$N_c = N_i + N_m + N_f$$

which was cited earlier. Stanford (1973) incorporated the efficiency (e) of crop recovery of each of the nitrogen fractions as:

$$N_c = e_iN_i + e_mN_m + e_fN_f$$

However, direct simultaneous measurements of each of these components in the field have not been attempted. This warrants priority in future crop-soil research.

Present methods are based on laboratory (i.e. short-term incubation) estimates of one or more of the components (e.g. Steele *et al.,* 1982a; Quin *et al.,* 1982). A more logical approach would be to measure N_i and N_m directly in the field to establish a field model. In the past, most predictive methods were established first in the laboratory followed by glasshouse and field experiments (see Bremner, 1965; Stanford, 1982). This approach has to rely on empirical interpretations of field events. What is needed are direct quantitative measurements of field processes to formulate a field model which could be simulated for routine uses (Tanji, 1982; Hauck and Tanji, 1982). An alternative approximation of N_m may also be achieved by the measurement of field micro-climatic data to estimate soil nitrogen mineralization in the field (Hart and Goh, 1980) together with the use of long-term weather forecasts.

Stanford (1982) assumed that the fractional efficiencies of crop nitrogen recovery of the various nitrogen components are the same as that of nitrogen fertiliser (i.e. $e_i = e_m = e_f$). These efficiences have not been directly measured in the field and would require using the ^{15}N tracer technique (Goh, 1982b). The recovery of fertiliser nitrogen by crops (i.e. e_f) has been extensively studied (e.g. Hauck, 1971; Hauck and Bremner, 1976; Tinker, 1979; Legg and Meisinger, 1982). Limited evidence from separate studies tend to support the view that fractional efficiencies of crop nitrogen recovered may by quantitatively different. For example, amounts of nitrogen recovered by wheat from ^{15}N-labelled legume material added to cropping soils in the field (Ladd *et al.,* 1981) are considerably lower than those commonly found for the recovery of nitrogen fertiliser (Legg and Meisinger, 1982). Climate and soil texture were cited as the main factors affecting wheat recovery of nitrogen from legume material while management (i.e. rate, form, method and time of fertiliser application) and growing conditions (e.g. soil properties, irrigation) are regarded as important in the recovery of fertiliser nitrogen (Olsen and Kurtz, 1982).

Tinker and Widdowson (1982) stated that 3 conditions must be satisfied if effective maximum yield of wheat is to be realised. These are:

(i) The rigid control of the use of nitrogen fertiliser.
(ii) The supply of nitrogen from the soil and fertiliser must be sufficient to avoid the crop running short of nitrogen.
(iii) The timing of nitrogen fertiliser application must be adjusted to the growth stage of the crop and the level of nitrate nitrogen in the soil.

These objectives are most likely to be attained if periodic monitoring of the nitrogen status of a crop during growth is conducted. As pointed out earlier, sap analysis for nitrate nitrogen forms part of the routine procedure for recommending supplementary nitrogen feeding of wheat crops in West Germany (Jungk and Wehrmann, 1978; Becker and Aughammer, 1982). Further development in this aspect of research is warranted.

Another important future research priority is the incorporation of the nitrogen prediction model into a wider modelling system which facilitates the linking of soil nitrogen cycling processes, environmental parameters, management factors and plant yield responses into a calculating procedure. This approach makes the predictions more realistic in terms of the total cropping system.

The requirements of a crop for nitrogen cannot be isolated from the multitude of processes and factors which affect its availabiltiy, uptake and utilization by the crop. The extent of recovery of a specific form of soil nitrogen (e.g. residual nitrate) by a crop, other than determined by crop demands for nitrogen, is primarily dependent not only on the presence of that nitrogen form in the soil but also on the opposing processes (e.g. volatilization, denitrification, leaching, immobilization) which operate to deplete its presence. These processes constitute the wider aspects of the soil nitrogen cycle. Simple leaching and volatilization models for nitrogen in soils are discussed at this conference (see Cameron, 1983; Sherlock and Goh, 1983). Comprehensive crop models which attempt to link some of the soil-plant-environmental factors have been presented elsewhere (e.g. Greenwood *et al.,* 1974; Campbell, 1978; Tanji, 1983; Hauck and Tanji, 1982; Jenkinson, 1982; Greenwood, 1982). Future research in modelling should incorporate in the model the effects of nitrogen on plant yield components, nitrogen grain yields and interactions of nitrogen application with management (e.g. irrigation), soil, and environmental factors.

In New Zealand cropping systems, nitrogen is mainly derived from soil organic nitrogen accumulated during the pasture phase of the crop rotation. Fertiliser nitrogen is only used as an adjunct to soil organic nitrogen mainly in the second and subsequent crops. Thus, the status and availability of soil nitrogen is highly dependent on the nature and duration of each of the different phases in the crop rotation used. The place of the crop in the rotation is often one of the main determining factors governing the use of nitrogen fertiliser as pointed out earlier. The advantage of the pasture phase has long been recognised in arable farming (see Lynch, 1959; Stephen, 1980, 1982). According to Herridge (1982), crop sequence research can lead to the identification of an efficient cropping system for farmers to use to optimise crop yield while maintaining long-term productivity. Greenland (1971) demonstrated that one can calculate the lengths of pasture and cropping phases required to attain an expected wheat yield when relying solely on the supply of legume-fixed nitrogen during the pasture phase. Russell (1975) proposed mathematical solutions in long-term experiments for estimating the "feed-back" effects of various crops. Taylor (1980) demonstrated the feasibility of using new legume ley systems in Northland and Waikato to supply nitrogen to crops. However, crop sequence research involving field measurements of soil nitrogen dynamics and status similar to those recently conducted in Rothamsted (Jenkinson, 1982) have not been conducted in New Zealand. Construction of nitrogen budgets (gains and losses) and cycling during each crop rotation phase requires research attention.

Among arable crops, research priority should first be given to horticultural crops because of their export potential followed by wheat and other arable crops. As pointed out earlier, horticultural research is still in its infancy and, in spite of recent interest in horticultural crop production and the relatively larger quantities of nitrogen fertilisers being used compared with agricultural crops, very little is known about their nitrogen requirements. As is often the case in practice, parallel development and research occur simultaneously with most arable crops and the question of crop priority is of minor importance.

CONCLUSIONS

This review and appraisal reveal the following:

1. Nitrogen is usually identified as the major nutrient in determining crop yield and quality.
2. To maximise crop yield, effective control of nitrogen supply to crops is vital. This requires the development of a reliable method for estimating nitrogen fertiliser requirements of arable crops.
3. Numerous studies overseas in the last 30 years involving many laboratory, glasshouse and limited field experiments have not been generally successful in finding a reliable predictive method largely because of their empirical nature and the lack of resemblance to actual field situations.
4. Research in New Zealand on this topic is relatively meagre and recent. Although some advances have been made, the methods used are based on laboratory estimation of the field situation and thus their reliability has yet to be tested.
5. A rational approach to the problem is suggested. This would involve direct field measurements of the major categories of plant-available nitrogen in the soil (i.e. residual nitrogen + mineralized nitrogen + fertiliser nitrogen), their recovery by the crop, and relating these to crop nitrogen uptake and yield to establish a quantitative model for practical use in the field. This should be conducted at first with a single crop in a limited number of soil types and climatic conditions. The model can then be tested across a range of soil, crop and climitic conditions before being simulated for routine fertiliser recommendations.
6. As a long-term objective, the model can be improved by linking nitrogen predictions to a wider model which incorporates other soil, plant, management, and environmental factors which affect crop yield responses and, if necessary, incorporating changes in soil nitrogen budgets and dynamics arising from different phases of the crop rotation sequence.
7. Plant analysis should be used to monitor periodically the adequacy of nitrogen in the crop especially at sensitive growth stages, to determine the need for supplementary feeding with nitrogen fertilisers.

REFERENCES

Alexander, M. 1977 "Introduction to Soil Microbiology". Second Edition, John Wiley and Sons, New York, 467 p.

Bartholomew, W.V. 1965. Mineralization and immobilization of nitrogen in the decomposition of plant and animal residues. *In* "Soil Nitrogen" Ed. W.V. Bartholomew and F.E. Clark. *American Society of Agronomy Monograph 10:* 285-306.

Becker, F.A., Aufhammer, W. 1982. Nitrogen requirements of winter wheat in the Federal Republic of Germany. *The Fertiliser Society Proceedings, London 211:* 33-66.

Benzian, B., Lane, P. 1982. Effects of husbandry treatments on nitrogen concentration of grain and related yields in winter wheat experiments made in South-East England. *Journal of Science, Food and Agriculture 33:* 1063-1071.

Bradenburg, W. 1980. "Outdoor Vegetable Growing". Canterbury Growers' Society, Christchurch. 304 p.

Bremner, J.W. 1965. Nitrogen availability indexes. *In* "Methods of Soil Analysis" Part 2. Eds. C.A. Black, D.D. Evans, J.L. White, L.E. Ensminger and F.E. Clark. *American Society of Agronomy Monograph 9:* 1324-2345.

Broadbent, F.E., Jackman, R.H., McNicoll, J. 1964. Mineralization of carbon and nitrogen in some New Zealand allophanic soils. *Soil Science 98:* 118-128.

Broadbent, F.E., Nakashima, T. 1971. Effect of added salts on nitrogen mineralization in three California soils. *Soil Science Society of America Proceedings 36:* 457-460.

Brockman, J.S. 1974. Quantity and timing of fertiliser nitrogen for grass and grass/clover swards. *The Fertiliser Society Proceedings, London 142:* 5-13.

Cameron, K.C. 1983. Nitrogen leaching: some fundamentals. *Proceedings Agronomy Society of N.Z. 13.*

Campbell, C.A. 1978. Soil organic carbon, nitrogen and fertility. *In* "Soil Organic Matter" Eds. M. Schnitzer and S.U. Khan. Elsevier Scientific Publishing Company, New York. pp. 137-271.

Campbell, C.A., Biederbeck, V.O., Hinman, W.C., 1975. Relationships between nitrate in summer-fallowed surface soil and some environmental variables. *Canadian Journal of Soil Science 55:* 213-223.

Campbell, C.A., Myers, R.J.K. and Weier, K.L. 1981. Potentially mineralizable nitrogen, decomposition rates and their relationship to temperature for five

Queensland soils. *Australian Journal of Soil Research 19:* 323-332.

Carter, J.N., Jensen, M.E., Bosma, S.M. 1974. Determining nitrogen fertiliser needs for sugar beets from residual nitrate and mineralizable nitrogen. *Agronomy Journal 66:* 319-323.

Carter, J.N., Westermann, D.T., Jensen, M.E., Bosma, S.M. 1975. Predicting nitrogen fertiliser needs for sugar beets from residual nitrate and mineralizable nitrogen. *Journal of American Society Sugar Beet Technology 18:* 232-244.

Cassman, K.G., Munns, D.N. 1980. Nitrogen mineralization as affected by soil moisture, temperature and depth. *Soil Science Society America Journal 44:* 1233-1237.

Cooke, G.W. 1979. Some priorities for British soil science. *Journal of Soil Science 30:* 187-213.

Cornforth, I.S. 1980. A simple test for nitrogen status of plants. *N.Z. Journal of Agriculture,* November 1980: 39-41.

Cornforth, I.S., Sinclair, A.G. (Eds.) 1982. "Fertiliser and lime recommendations for pastures and crops in New Zealand." N.Z. Ministry of Agriculture and Fisheries, Wellington. 66p.

Dahnke, W.C., Vasey, E.H. 1973. Testing soils for nitrogen. *In* "Soil Testing and Plant Analysis" Eds. L.M. Walsh and J.D. Beaton. Soil Science Society of America, Madison, Wisconsin. pp. 97-114.

Dougherty, C.T., Scott, W.R., Langer, R.H.M. 1975. Effects of sowing rate, irrigation and nitrogen on the components of yield of spring-sown semidwarf and standard New Zealand wheats. *N.Z. Journal of Agricultural Research 18:* 197-207.

Douglas, J.A. 1968. Fertiliser trials on cereals in North Otago. *N.Z. Journal of Agriculture 116 (3):* 82-83.

Drewitt, E.G. 1979. Relationships between grain yield, grain nitrogen % and grain weight in irrigated and non-irrigated late winter and spring-sown Karamu wheat. *N.Z. Journal of Experimental Agriculture 7:* 169-173.

Drewitt, E.G., Rickard, D.S. 1973. The effect of irrigation on the yield components and nitrogen uptake of three wheat cultivars. *Proceedings Agronomy Society of N.Z. 3:* 73-80.

Evans, L.T., Wardlaw, I.F., Fischer, R.A. 1975. Wheat. *In* "Crop Physiology, Some Case Histories". Ed. L.T. Evans, Cambridge University Press, London. pp. 101-149.

Farooqi, M.A.F., Hanif, M., de Mooy, C.J. 1983. Nitrogen mineralization potential and urea hydrolysis under aerobic and anaerobic conditions. *Communications in Soil Science and Plant Analysis 14:* 29-47.

Feyter, C., Cossens, G.G. 1977. Effect of rates and methods of nitrogen application on grain yields and yield components of spring-sown wheat in South Otago, New Zealand. *N.Z. Journal of Experimental Agriculture 5:* 371-376.

Feyter, C., Cossens, G.G., Risk, R.H. 1977. Effects of rainfall on nitrogen responses of spring-sown wheats. *N.Z. Journal of Experimental Agriculture 5:* 161-165.

Fox, R.H., Piekielek, W.P. 1978. A rapid method for estimating the nitrogen supplying capability of a soil. *Soil Science Society of America Journal 42:* 751-753.

Fried, M., Broeshart, H. 1967. "The Soil-Plant System In Relation To Inorganic Nutrition". Academic Press, New York. 358 p.

Gasser, J.K.R. 1982. Agricultural productivity and the nitrogen cycle. *In* "The Nitrogen Cycle". Eds. W.D.P. Stewart and T. Rosswall. *Philosophical Transactions of the Royal Society of London Series B, 296:* 303-314.

Geist, J.M., Reuss, J.O., Johnson, D.D. 1970. Prediction of nitrogen fertiliser requirements of field crops. II. Application of theoretical models to malting barley. *Agronomy Journal 62:* 385-389.

Goh, K.M. 1982a. Losses of nitrogen from arable systems. *In* "Nitrogen Balances In New Zealand Ecosystems". Eds. P.W. Gandar. Plant Physiology Division, D.S.I.R., Palmerston North. pp. 161-167.

Goh, K.M. 1982b. The significance of the ^{15}N technique in nitrogen balance studies. *In* "Nitrogen Balances In New Zealand Ecosystems". Ed. P.W. Gandar. Plant Physiology Division, D.S.I.R., Palmerston North. pp 179-183.

Goh, K.M., Edmeades, D.C. 1979. Distribution and partial characterization of acid hydrolysable organic nitrogen in six New Zealand soils. *Soil Biology Biochemisty 11:* 127-132.

Goh, K.M., Vityakon, P. 1983. Effects of fertilisers on vegetable production. I. Yield of spinach and beetroot as affected by rates and forms of nitrogenous fertilisers. *N.Z. Journal of Agricultural Research 26* (In Press).

Greenland, D.J. 1971. Changes in the nitrogen status of soils under pasture with special reference to the maintenance of the fertility of Australian soils used for growing wheat. *Soils and Fertilisers 34:* 237-251.

Greenwood, D.J. 1982. Modelling of crop responses to nitrogen fertiliser. *In* "The Nitrogen Cycle". Eds. W.D.P. Stewart and T. Rosswall. *Philosophical Transactions of the Royal Society of London Series B, 296:* 351-362.

Greenwood, D.J., Wood, J.T., Cleaver, T.J. 1974. A dynamic model for the effects of soil and weather conditions on nitrogen response. *Journal of Agricultural Science, Cambridge 82:* 455-467.

Greenwood, P.B., Quin, B.F.C., Sinclair, A.G. 1982. Wheat, barley and oats. *In* "Fertiliser Recommendations For Pastures And Crops In New Zealand" Eds. I.S. Cornforth and A.G. Sinclair. N.Z. Ministry of Agriculture and Fisheries, Wellington. pp. 26-27.

Gregory, P.J., Marshall, B., Biscoe, P.V. 1981. Nutrient relations of winter wheat. 3. Nitrogen uptake, photosynthesis of flag leaves and translocation of nitrogen to grain. *Journal of Agricultural Science, Cambridge 96:* 539-547.

Harmsen, G.W., Kolenbrander, G.J. 1965. Soil inorganic nitrogen. *In* "Soil Nitrogen". Eds. W.V. Bartholomew and F.E. Clark. *American Society of Agronomy, Monograph 10:* 43-92.

Harmsen, G.W., Van Schreven, D.A. 1955. Mineralization of organic nitrogen in soils. *Advances in Agronomy 7:* 299-398.

Hart, P.B.S., Goh, K.M. 1980. Regression equations to monitor inorganic nitrogen changes in fallow and wheat soils. *Soil Biology Biochemistry 12:* 147-151.

Hart, P.B.S., Goh, K.M., Ludecke, T.A. 1979. Nitrogen mineralization in fallow and wheat soils under field and laboratory conditions. *N.Z. Journal of Agricultural Research 22:* 115-125.

Hauck, R.D. 1971. Quantitative estimates of nitrogen-cycle processes: Concepts and review. *In* "Nitrogen-15 in Soil-Plant Studies". International Atomic Energy Agency, Vienna. pp 65-80.

Hauck, R.D., Bremner, J.M. 1976. Use of tracers for soil and fertiliser nitrogen research. *Advances in Agronomy 28:* 219-266.

Hauck, R.D., Tanjii, K.K. 1982. Nitrogen transfers and mass balances. *In* "Nitrogen In Agricultural Soils". Ed. F.J. Stevenson. *American Society of Agronomy Monograph 22:* 891-925.

Haynes, R.J., Goh, K.M. 1978. Ammonium and nitrate nutrition of plants. *Biological Review 53:* 465-510.

Herlihy, M. 1979. Nitrogen mineralization of varying texture, moisture and organic matter. I. Potential and experimental values in fallow soils. *Plant And Soil 53:* 255-267.

Herridge, D.F. 1982. Crop rotations involving legumes. *In* "Nitrogen Fixation In Legumes". Ed. J.M. Vincent. Academic Press, Sydney. pp. 253-261.

Hudson, A.W., Woodcock, J.W. 1934. Wheat manuring experiments in the South Island. A summary of eleven season research. *N.Z. Journal of Agriculture 48:* 321-330.

James, D.W. 1978. Diagnostic soil testing for nitrogen availability: The effects of nitrogen fertiliser rate, time and method of application and cropping pattern on residual soil nitrogen. *Utah Agricultural Experimental Station, Utah Bulletin 497.*

James, D.W., Nelson, C.E., Halversen, A.R. 1967. Soil testing for residual nitrates as a guide for nitrogen fertilisation of sugarbeets. *Washington Agricultural Experimental Station Circular 480.*

Jenkinson, D.S. 1971. Studies on the decomposition of ^{14}C-labelled organic matter in soil. *Soil Science 111:* 64-70.

Jenkinson, D.S. 1982. The nitrogen cycle in long-term field experiments. *In* "The Nitrogen Cycle". Eds. W.D.P. Stewart and T. Rosswall. *Philosophical Transactions of the Royal Society of London Series B 296:* 563-571.

Jungk, A., Wehrmann, J. 1978. Determination of nitrogen requirements by plant and soil analysis. *In* "Plant Nutrition". Eds. A.R. Ferguson, R.L. Bieleski and I.B. Ferguson. *Proceedings 8th International Coloquium Plant Analysis and Fertiliser Problems, Auckland 1:* 209-224.

Keeney, D.R., Bremner, J.M. 1966. Comparisons and evaluation of laboratory methods of obtaining an index of soil nitrogen availability. *Agronomy Journal 58:* 498-503.

Kirkby, E.A. 1981. Plant growth in relation to nitrogen supply. *In* "Terrestrial Nitrogen Cycles". Eds. F.E. Clark and T. Rosswall. *Ecological Bulletin (Stockholm) 33:* 249-267.

Kolenbrander, G.J. 1973. Fertilisers, farming practice and water quality. *The Fertiliser Society Proceedings, London 135:* 4-36.

Ladd, J.N., Oades, J.M., Amato, M. 1981. Distribution and recovery of nitrogen from legume residues decomposing in soils sown to wheat in the field. *Soil Biology Biochemistry 13:* 251-256.

Langer, R.H.M. 1980. Components of wheat yield. *Proceedings Lincoln College Farmers' Conference 29:* 134-141.

Laura, R.D. 1975. The "A value" and the priming effect of nitrogen fertilisers on soil nitrogen. *Soil Science Society of America Proceedings 39:* 596.

Legg, J.O., Meisinger, J.J. 1982. Soil nitrogen budgets. *In* "Nitrogen In Agricultural Soils". Ed. F.J. Stevenson. *American Society of Agronomy, Monograph 22:* 467-502.

Legg, J.O., Stanford, G. 1967. Utilization of soil and fertiliser nitrogen by oats in relation to the available nitrogen status of soils. *Soil Science Society of America Proceedings 31:* 215-219.

Leggett, G.E. 1959. Relationships between wheat yield, available moisture and available nitrogen in Eastern Washington dryland areas. *Washington Agricultural Experimental Station Bulletin 609.*

Ludecke, T.E. 1974. Prediction of grain yield responses in wheat to nitrogen fertilisers. *Proceedings Agronomy Society of N.Z. 4:* 27-29.

Ludecke, T.E., Tham, K.C. 1971. Seasonal variations in the level of mineral nitrogen in two soils under different management systems. *Proceedings Agronomy Society of N.Z. 1:* 203-214.

Lynch, P.B. 1959. Wheat manuring in New Zealand. *N.Z. Wheat Review 1:* 44-49.

MAFF 1967. Fertiliser recommendations for agricultural and horticultural crops, NAAS Advisory Paper No. 4, Ministry of Agriculture, Fisheries and Food, London.

MAFF 1979. Fertiliser recommendations. GF 1. London. HMSO.

Malden, G.W. 1982. Fertiliser Handbook. Second Edition. The New Zealand Farmers' Fertiliser Co. Ltd, Auckland. 48 p.

McLeod, C.C. 1962. Fertilisers on cereals. *Proceedings Lincoln College Farmers' Conference 12:* 38-44.

Michrina, B.P., Fox, R.H., Piekielek, W.P. 1981. A comparison of laboratory, greenhouse and field indicators of nitrogen availability. *Communications in Soil Science and Plant Analysis 12:* 519-535.

Minard, H.R.G. 1977. Nutrition *In* Proceedings Brassica Short Course No. 4, Massey University, Palmerston North. pp. 21-24.

Needham, P. 1982. The role of nitrogen in wheat production: Response, interaction and prediction of nitrogen requirements in the U.K. *The Fertiliser Society Proceedings, London 211:* 125-147.

Olson, R.A., Kurtz, L.T. 1982. Crop nitrogen requirements, utilization and fertilization. *In* "Nitrogen in Agricultural Soils". Ed. F.J. Stevenson. *American Society of Agronomy, Monograph 22:* 567-604.

Oyanedel, C., Rodriguez, J. 1977. Estimation of nitrogen mineralization in soils. *Cienc. Investi. Agraria 4:* 33-44.

Prado, O., Rodriguez, J. 1978. Nitrogen fertiliser requirement estimates of wheat. *Cienc. Investi. Agraria 5:* 29-40.

Quin, B.F. 1982. Sodium bicarbonate extraction of soils for the prediction of crop nitrogen requirements. *In* "Nitrogen Balances in New Zealand Ecosystems". Ed. P.W. Gandar. Plant Physiology Division, D.S.I.R, Palmerston North. pp. 205-208.

Quin, B.F., Drewitt, E.G. 1979. The growth, nitrogen uptake and yield of spring sown wheat on Lismore silt loam. *Proceedings Agronomy Society of N.Z. 9:* 133-138.

Quin, B.F., Drewitt, E.G., Stephen, R.C. 1982. A soil incubation test for estimating wheat yields and nitrogen requirements. *Proceedings Agronomy Society of N.Z. 12:* 35-40.

Reuss, J.O., Geist, J.M. 1970. Predictions of nitrogen requirements of field crops. I. Theoretical model of nitrogen release. *Agronomy Journal 62:* 381-384.

Ris, J., Smilde, K.W., Wijen, G. 1981. Nitrogen fertiliser recommendations for arable crops as based on soil analysis. *Fertiliser Research 2:* 21-32.

Robinson, J.B.D. 1975. The soil nitrogen index and its calibration with crop performance to improve fertiliser efficiency on arable soils. Commonwealth Bureau of Soils, Special Publication No. 1, Commonwealth Agricultural Bureau, England. 53 p.

Russell, J.S. 1975. A mathematical treatment of the effect of cropping system on soil organic nitrogen in two long-term sequential experiments. *Soil Science 120:* 37-44.

Scott, W.R. 1977. Components of Grain Yield in Wheat. Ph.D. Thesis, Lincoln College. 167 p.

Scott, W.R. 1981. Improving wheat quality by agronomic management. *Proceedings Agronomy Society of N.Z. 11:* 91-97.

Scott, W.R., Dougherty, C.T., Langer, R.H.M. 1977. Development and yield components of high yielding wheat crops. *N.Z. Journal of Agricultural Research 20:* 205-212.

Sherlock, R.R., Goh, K.M. 1983. A simple mathematical model simulating ammonia volatilization losses in the field. *Proceedings Agronomy Society of N.Z. 13.*

Smith, S.J., Young, L.B., Miller, G.E. 1977. Evaluation of soil nitrogen mineralization potential under modified field conditions. *Soil Science Society America Journal 41:* 74-76.

Soper, R.J., Huang, P.M. 1963. The effect of nitrate nitrogen in the soil profile on the response of barley to fertiliser nitrogen. *Canadian Journal of Soil Science 4:* 350-358.

Soper, R.J. Racz, G.J., Fehr, P.I. 1971. Nitrate nitrogen in the soil as a means of predicting the fertiliser nitrogen requirements of barley. *Canadian Journal of Soil Science 51:* 45-49.

Stanford, G. 1973. Rationale for optimum nitrogen fertilisation in corn production. *Journal of Environmental Quality 2:* 159-166.

Stanford, G. 1982. Assessment of soil nitrogen availability. *In* "Nitrogen in Agricultural Soils". Ed. F.J. Stevenson. *American Society of Agronomy, Monograph 22:* 651-688.

Stanford, G., Smith, S.J. 1972. Nitrogen mineralization potentials of soils. *Soil Science Society of America Proceedings 36:* 465-472.

Stanford, G., Carter, J.N., Smith, S.J. 1974. Estimates of potentially mineralizable soil nitrogen based on short term incubations. *Soil Science Society of America Proceedings 38:* 99-102.

Stanford, G., Carter, J.N., Westermann, D.T., Meisinger, J.J. 1977. Residual nitrate and mineralizable soil nitrogen in relation to nitrogen uptake by irrigated sugar beets. *Agronomy Journal 69:* 303-308.

Stanford, G., Frere, M.H., Schwaininger, D.H. 1973. Temperature coefficient of soil nitrogen mineralization. *Soil Science 115:* 321-323.

Steele, K.W. 1981. Nitrogen. *In* "Fertiliser Recommendations for Pastures and Crops in New Zealand". Eds. I.S. Cornforth and A.G. Sinclair. N.Z. Ministry of Agriculture and Fisheries, Wellington. pp. 28-29.

Steele, K.W., Cooper, D.M. 1980. Reducing fertiliser applications to maize. *Proceedings 1980 Ruakura Farmers' Conference:* 25-32.

Steele, K.W., Cooper, D.M., Dyson, C.B. 1982a. Estimating nitrogen fertiliser requirements in maize grain production. I. Determination of available soil nitrogen and prediction of grain yield increase to applied nitrogen. *N.Z. Journal of Agricultural Research 25:* 199-206.

Steele, K.W., Cooper, D.M., Dyson, C.B. 1982b. Estimating nitrogen fertiliser requirements in maize grain production. 2. Estimates based on ear leaf and grain nitrogen concentrations. *N.Z. Journal of Agricultural Research 25:* 207-210.

Stephen, R.C. 1980. Fertilisers for wheat. *Proceedings Lincoln College Farmers' Conference 29:* 50-58.

Stephen, R.C. 1982. Nitrogen fertilisers in cereal production. *In* "Nitrogen Fertilisers in New Zealand Agriculture". Ed. P.B. Lynch. N.Z. Institute of Agricultural Science, Wellington. pp. 77-93.

Stevenson, F.J. 1982a. Origin and distribution of nitrogen in soil. *In* "Nitrogen in Agricultural Soils". Ed. F.J. Stevenson. *American Society of Agronomy Monograph 22:* 1-42.

Stevenson, F.J. 1982b. Organic forms of soil nitrogen. *In* "Nitrogen in Agricultural Soils". Ed. F.J. Stevenson. *American Society of Agronomy Monograph 22:* 721-772.

Taylor, A.O. 1980. Why use legumes in intensive forage crop production systems. *Proceedings Agronomy Society of N.Z. 10:* 49-53.

Tinker, P.B.H. 1979. Uptake and consumption of soil nitrogen in relation to agronomic practice. *In* "Nitrogen Assimilation of Plants". Eds. E.J. Hewitt and C.V. Cutting. Proceedings of Sixth Symposium, Long Ashton Research Station, Bristol, Academic Press, London. pp. 101-122.

Tinker, P.B.H., Widdowson, F.V. 1982. Maximising wheat yields and some causes of variation. *The Fertiliser Society Proceedings, London 211:* 149-184.

Verstraete, W. 1981. Nitrification in agricultural systems: Call for control. *In* "Terrestrial Nitrogen Cycles". Eds. F.E. Clark and T. Rosswall. *Ecological Bulletin (Stockholm) 33:* 565-572.

Wallace, E.G.R. 1975. Vegetable Growers Handbook. Henry H. York Co. Ltd., Petone, New Zealand. 78p.

Walker, T.W. 1969. Nitrogen fertilisers in Canterbury. *Proceedings Lincoln College Farmers' Conference 19:* 99-104.

Walker, T.W., Ludecke, T.E. 1982. An economic evaluation of the use of nitrogen fertilisers on field crops in New Zealand. *In* "Nitrogen Fertilisers In New Zealand Agriculture". Ed. P.B. Lynch. N.Z. Institute of Agricultural Science, Wellington. pp. 95-119.

Webster, A.B. 1969. Manuring and spacing experiments of vegetables. *N.Z. Journal of Agricultural Research 12:* 381-416.

Westerman, R.L., Kurtz, L.T. 1973. Priming effect of ^{15}N-labelled fertiliser on soil nitrogen in field experiments. *Soil Science Society America Proceedings 37:* 725-727.

Westerman, R.L., Tucker, T.C. 1974. Effects of salts and salts plus nitrogen-15-labelled ammonium chloride in mineralization of soil nitrogen, nitrification and immobilization. *Soil Science Society of America Proceedings 38:* 602-605.

Whitehead, D.C. 1981. An improved chemical extraction method for predicting the supply of available soil nitrogen. *Journal of Science, Food and Agriculture 32:* 359-365.

Whitehead, D.C., Barnes, R.J., Morrison, J. 1981. An investigation of analytical procedures for predicting soil nitrogen supply to grass in the field. *Journal of Science, Food and Agriculture 32:* 211-218.

Wilson, G.J. 1975. Fertiliser requirements for vegetables at Pukekohe. *N.Z. Fertiliser Journal 45:* 21-22.

Withers, N.J. 1982. Sap tests for measuring nitrogen status of cereals. *Proceedings Agronomy Society of N.Z. 12:* 41-44.