A SOIL INCUBATION TEST FOR ESTIMATING WHEAT YIELDS AND NITROGEN REQUIREMENTS

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ABSTRACT

A soil incubation test for predicting the yield of wheat without nitrogen (N) fertiliser has been developed from data on 31 trials over a two year period. Nitrate- and ammonium-N are determined before and after a 7-day incubation of the field-moist soil sample (0-15 cm depth) at 37 °C. A combination of initial mineral N (IN) and twice the increase in mineral N after incubation (ΔN) was most closely related to yield.

The amount of N required to maximise yield is calculated from the predicted yield without N (Yo), the known potential yield for the area (Yp), and the efficiency of conversion of N to grain, which was found to be linear over most of the range of N response. The procedure will improve the precision in estimating N fertiliser requirements for wheat and will be refined as further data becomes available.

Additional Key Words: cereal crops, fertilisers, plant nutrients, yield prediction.

INTRODUCTION

Nitrogen (N) is the most important fertiliser element to consider for cereal crops. The use of insufficient N fertiliser can greatly restrict yield and profit, while excessive useage is wasteful, costly, may reduce yield and contribute to deterioration in ground water quality. Nevertheless, recommendations for its use have been very imprecise, being based largely on paddock hisotry and field trial information, generally without any basis for extrapolation of the results.

In recent years, a Canterbury fertiliser manufacturer has made N fertiliser recommendations for winter-sown wheat based on the concentration of nitrate-N (NO_3-N) in the 0-60 cm soil depth in early spring. Lukecke (1974) had demonstrated a relationship between grain yield response and soil NO_3-N levels in early spring. Although the 0-20 cm depth was as closely correlated with yield response as the 0-60 cm depth, the latter was adopted. It has been argued that the shallow depth could underestimate the soil NO_3-N supply in years when leaching had led to accumulations at lower depths but the question of whether this deeper NO_3-N would actually be recovered by the crop was not considered.

Although a distinct improvement on 'paddock history' methods of making N recommendations, the "deep nitrate" test had several major drawbacks. It did not provide any indication of the ability of the soil to release mineral N during the growth of the crop. Levels of soil NO_3-N present in early spring frequently represent less than 25% of the total N mineralised from soil organic N during the crop growth (Quin and Drewitt, 1979). Fluctuations in the NO_3 level at one point in spring from year to year were not necessarily therefore reflected in differences in N response trends between years.

Major fluctuations from week to week due to leaching and mineralisation made recommendations based on a NO_3-N level at an arbitrary point in time difficult. In wetter than average winters, where leaching had reduced NO_3-N to low levels in all paddocks regardless of their fertility status, recommendations could only be based on paddock history. However, a comparison in a drier year showed that the NO_3-N levels in paddocks out of long term pasture showed that same mean and range as those following 2 cereal crops (12 μ g/g, range 4-29, and 13 μg/g, range 4-28 respectively). This illustrates the range of N depletion by crops and of fertility building by pastures, and highlights the shortcomings of the 'paddock history' approach.

Feyter *et al.* (1977) established relationships between N responses on spring-sown wheat and winter rainfall in Otago and Southland. This was basically a broader application of the 'deep-nitrate' soil test approach; the higher the rainfall, the greater the leaching of NO_3-N. Good relationships were established for second crops; first crops generally showed no response to N. Relationships were far more obscure for third year crops, no doubt because of increasing variability in N fertility status between paddocks. For April-June rainfalls of 200 mm, grain responses to 75 kg N/ha on third year crops varied from 100-1400 kg/ha. In other words, although the method predicted overall trends in responsiveness to N, it was not sufficiently precise to predict requirements on a paddock scale (Feyter and Cossens, 1977).

A great deal of effort in many countries has been put into developing soil N tests for predicting crop requirements. While incubation techniques are generally regarded as being the most accurate, the long incubation times usually considered to be necessary have prevented their commercial use, and chemical extractions of 'labile' N have received most attention (Whitehead, 1981). In New Zealand, Steele *et al.* (1982) used the mineral N content of air-dried soils to estimate maize N requirements and commented that the air drying was in effect a short (although uncontrolled) incubation test that gave superior results compared with the mineral N content of the fresh soil. Quin (1982a) concluded that incubation techniques were likely to be superior to chemical extraction methods.

This paper reports the development of an estimate procedure for wheat crops based on soil analysis of NO_3-N plus ammonium-N (NH_4-N) before and after a 7 day incubation of the field-moist soil at 37 °C. Initial NO_3-N plus NH_4-N is hereafter abbreviated to IN. The increase in mineral N during the incubation (ΔN) reflects the ability of the soil organic N to release mineral N during the growth of the crop.

MATERIALS AND METHODS

Soil samples were obtained from a total of 31 trials examining rates of N fertiliser on wheat conducted in the South Island during either 1980/81 or 1981/82. Soil Quick Tests were used to ensure that basal applications of other nutrients were sufficient to avoid deficiencies other than N. Trials severely affected by moisture stress were excluded. For each soil sample, 8-10 soil cores (2.5 cm diam) were collected at random from each experimental area in early spring (late August/early September for Canterbury, later September for Southland). In some of the trials, additional samplings were made on other occasions. The 0-15 depth was sampled on all trials; the 15-30, 30-45, and 45-60 cm depths were also sampled at most sites.

The field-moist soil was hand sieved through a 2 mm sieve, sub-sampled, and analysed for 2M KOl — extractable NO_3-N and NH_4-N (1:5 soil solution ratio, 60 min shaking). The remainder of the sub-sample was incubated in thin (0.5 mil thickness) polyethylene plastic bags before analysis for NO_3-N and NH_4-N. Plastic bags of this type allow sufficient oxygen to pass through the plastic film into the sample to maintain aerobic incubation, while adequately restricting the loss of moisture out from the sample (Bremner and Douglas, 1971).

NO_3-N and NH_4-N were determined on a Chemlab continuous flow system, after the method of Brown (1973). Another sub-sample was used to determine the soil moisture content. This was used to calculate NO_3-N and NH_4-N concentration on a μg/g dry soil basis.

Grain yields were generally determined by hand harvesting 1m^2 plots and threshing. Yields were adjusted to a dry basis.

RESULTS AND DISCUSSION

Parameters affecting the laboratory assessment of Δ N

Effect of soil moisture on Δ N value. To determine whether the time-consuming operation of wetting all samples to constant percentage of water holding capacity was necessary, replicate samples of a saturated Lismore silt loam soil were allowed to air-dry to varying degrees before incubation. The results (Table 1) demonstrate that at or above 40% available soil moisture there were no significant differences in the Δ N value and therefore the field-moist samples could be incubated directly in most cases.

TABLE 1: Effect of soil moisture on Δ N.

Available soil moisture (%)	0[a]	20	40	60	80	100[b]	120
N (μg/g)[c]	23 ±6	51 ±3	60 ±2	61 ±2	62 ±2	61 ±2	58 ±3

[a] wilting point
[b] field capacity
[c] increase in Δ N all as NO_3-N, except for 120% available soil moisture, where much of increase was as NH_4-N.

The results do however demonstrate how the incubation of an atypically dry sample can underestimate the mineralisation potential of the soil under conditions of adequate moisture.

Under the anaerobic conditions existing in the saturated soil, mineral N produced by mineralisation of organic N is not oxidised from NH_4-N to NO_3-N (Table 1). NH_4-N is less available for plant uptake than NO_3-N due to its adsorption onto the soil cation-exchange complex. However, rapid oxidation will occur as the soil moisture content drops through drainage and/or evapotranspiration.

Effect of incubation temperature on Δ N. The rate of mineralisation of soil organic N increases exponentially with increasing temperature (Table 2).

TABLE 2: Effect of incubation temperature on Δ N.

Temperature (°C)	5	10	15	25	37	42
N[a]	1.9 ±0.6	5 ±1.3	9 ±2.5	17 ±3.2	62 ±2.1	90 ±8.5

[a]Increase in Δ N all as NO_3-N, except for 42 °C where most of increase was as NH_4-N.

A temperature of 37 °C was selected for use because it gave a combination of high (and therefore easily measurable) ΔN and low variability, without significant drying of the sample occuring during the 7 days (see next section). The higher variability at temperatures 25 °C or below was thought to be a function of micro-maldistribution of plant litter which could cause an initial but variable lag in net mineralisation; it was assumed that at 37 °C the effect of this was minimised by the much greater total net mineralisation achieved (Quin, 1982a). The high variability at 42 °C is associated with the change from aerobic to anaerobic conditions (assessed by the increase in ΔN occuring predominantly as NH_4-N). These conditions presumably resulted from the flow of oxygen through the plastic bag into the sample being insufficient to keep pace with the rate of mineralisation of organic N to NH_4-N.

These results illustrate the necessity of close control of the incubation temperature. They also illustrate how small changes in soil temperatures in the field can greatly influence the rate of mineralisation. For example, for the month of October in Canterbury, a deviation of 1 °C from the mean soil temperature of 10 °C produces a deviation of ± 20% in the amount of N mineralised.

Effect of sample thickness on ΔN. For incubation at 37 °C, the optimum sample thickness was found to be 1.5-2.0 cm; significant drying of the sample occured at reduced thickness, while anaerobic conditions developed in the centre of the sample at greater thicknesses.

Relating IN and Δ N to paddock N fertility

Relevance of IN value. The IN content of the soil represents previous mineralisation, residual N fertiliser and animal urine-N. Typically, most of the IN will be present as NO_3-N, although previous applications of urea or sulphate of ammonia fertiliser may be present largely as NH_4-N. Very wet soils may also contain much of the IN as NH_4-N. Cultivation, particularly if preceeded or followed by a sudden increase in soil moisture through rainfall, can produce a rapid but temporary increase in the rate of mineralisation. As NO_3-N is easily leached, IN values are subject to rapid change.

The effect of paddock history on ΔN values — an example. Soil samples were taken from an area on the Winchmore Research Station which goes through a rotation of 4 years irrigated pasture followed by 2 years irrigated wheat or barley. At any one time, there are paddocks in the first to fourth year of pasture and first or second crop.

TABLE 3: Effect of paddock history on Δ N value.

(Lismore Silt Loam)						
	YEARS IN PASTURE				CEREAL CROPS	
	1	2	3	4	after one	after two
ΔN	36	45	53	61	53	31

The results (Table 3) demonstrate the accumulation of mineralisable N from a low ΔN of 31 μg/g following the second cereal crop to 61 after 4 years of pasture. The results also demonstrate that on this soil type (Lismore stony silt loam, a yellow grey earth), two years of good pasture are required to restore the N fertility depleted by one cereal crop.

Ratio for combining IN and Δ N. The procedure described in this paper was designed primarily for use in late winter/early spring, i.e. in the period after winter leaching, and when mineral N is at a maximum before crop N uptake is increasing more rapidly than is its production from soil organic N.

The combination of IN and Δ N used in the procedure should ideally therefore reflect the relative contribution of the IN and the mineral N to be produced through mineralisation during the growth of the crop.

Various field studies have demonstrated that mineralisation of organic N from the 0-15 cm depth of fertile South Island soil totals approximately 200-250 kg N/ha between early spring and harvest of the cereal crop (Ludecke and Tham, 1971; Hart *et al.*, 1979; Quin, 1982b). Assuming an average bulk density of approximately unity for the 0-15 cm depth of cultivated soils, this represents 130-160 μg/g of mineral N produced from the 0-15 cm depth between early spring and harvest. As ΔN values for fertile cereal-cropped soils ranged from 55-80 μg/g, it therefore seemed logical to combine IN (the actual mineral N initially present) with ΔN in the ratio of 1:2 in the procedure. Statistical validation of this approach was provided by correlations with grain yield with different combinations of IN and ΔN. (Table 4).

TABLE 4: Effect on altering combination of IN and Δ N on relationship with yield (29 sites).

Combination	r
IN	.55 *
IN + ΔN	.62 *
IN + 2ΔN	.71 **
IN + 3ΔN	.66.*
ΔN	.56 *

Expression of IN + 2ΔN as μg/g or kgN/ha. The only advantage in converting μg/g values to kgN/ha is to attempt an N budget or balance sheet. However, Quin and Drewitt (1979) and Quin (1982b) demonstrated that far more soil organic N is mineralised during the growth of the crop than can be accounted for by crop N content, leaching, and other obvious loss mechanisms. It was postulated that large scale losses of N from foliage to the atmosphere occur. These large but non-quantified losses prevent the estimation of mineralisation of soil N by crop N content.

The use of the 0-15 cm depth for IN + 2ΔN. The depths of soils used for cereal cropping vary markedly, as consequently does the relative contribution of the 0-15 cm depth to the total mineralisable N pool. The average in this study was 65%, with a range of 45-82% (Table 5).

TABLE 5: Percentage of total mineralisable N contributed from various soils depths.

Soil	Depth (cm)			
	0-15	15-30	30-45	45-60
Eyre stony silt loam	82	9	6	3
Lismore silt loam	75	16	7	2
Lyndhurst silt loam	54	30	10	6
Mayfield silt loam	46	37	12	5
Mean	64	23	9	4

This appears to cast doubt on the validity of using a constant (and rather shallow) 0-15 cm depth for all soils. However, deeper soils have a higher potential yield and, as described later, the potential yield estimate is an integral part of the procedure. In addition, the N fertility of the 0-15 cm depth is depleted much more rapidly and markedly by cropping than deeper depths and therefore most clearly reflects (or predicts) the actual yield, as shown in Table 6.

TABLE 6: Effect of increasing soil depth on relationship between yield and (IN + 2 ΔN) (20 sites).

Depth	r
0-15	.64**
0-30	.47*
0-45	.48*
0-60	.41*

Finally, although N fertiliser requirements may be overestimated in situations where NO--N has accummulated below 15 cm due to leaching (Ludecke and Tham, 1971), there is nonetheless no guarantee that the crop will be able to utilise deeper NO--N before it is leached beyond the root zone. This is presumably the reason why Ludecke (1974) found no improvement in correlation of soil NO--N and N response by increasing the sampling depth from 20 cm to 60 cm.

Relationship of IN + 2 ΔN to crop yield in absence of applied N fertiliser.

The relationship between crop yield (tonnes grain/ha) and the IN + 2 ΔN value was linear throughout the range of crop yields obtained, *viz* 2-10t (Fig. 1). This indicated that wheat crops are (provided moisture and other nutrients are non-limiting) capable of utilising for growth all the N that will become available during the growth of the crop. In other words, it is the climate, soil type and land use that control the maximum possible accummulation of mineralisable N in the soil, and these factors also control the potential yield of the wheat crop.

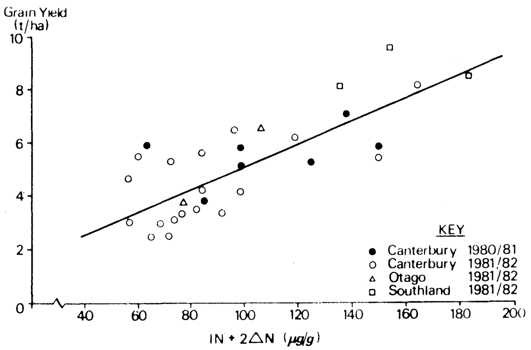

Figure 1: Relationship between wheat grain yield in the absence of N fertiliser (Yo) and IN + 2 ΔN:- Yo = 1.0 + 0.0417 (IN + 2 ΔN), r = 0.71**

The fact that the regression indicates some yield (1.0t/ha) theoretically obtainable at IN + 2ΔN = 0 reflects the fact that the N fertility of the 0-15 cm depth declines proportionately more rapidly than that at deeper depths due to greater rates of depletion; even if IN + 2 ΔN declined to zero for the 0-15 cm depth, a small yield would be sustained by N released from deeper depths.

PROCEDURE FOR CALCULATION OF OPTIMUM N APPLICATION

Components of procedure The procedure involves four steps:—

1. Assessment of potential yield (Yp) for the area (given adequate moisture, N and other nutrients);
2. Estimation of yield without N fertiliser (Yo) from Yo = 1.0 + 0.0417 (IN + 2ΔN).
3. Multiply Yp-Yo by 40 (Canterbury) or 50 (Otago/Southland) to obtain N requirement in kgN/ha.
4. Use IN value to decide whether N is required immediately (if IN very low), or whether application can be delayed (if IN is high) to reduce likelihood of leaching loss.

Response curves and efficiency of conversion of fertiliser N to grain yield.

All N response curves in this study with 4 or more rates, and others in the literature (Feyter and Cossens, 1977), were studied. It was apparent that N response curves were essentially linear with increasing N up until a yield within 0.5t/ha of the maximum, the conversion averaging 26 kg grain/kg N (39 kg N required per tonne grain response) for Canterbury and 21 kg grain/kg N (48 kg N required per tonne grain response) for Otago and Southland. The poorer efficiency in Otago and Southland may reflect greater leaching losses, differing growth patterns and different cultivars. Efficiency of utilisation dropped markedly for the last 0.5t/ha in yield increase, to less than 10 kg grain/kg N in all areas.

The linearity of the response curve simplifies the estimation of the N requirement. Because the efficiency drops for the last 0.5t, the procedure actually calculates the N requirement to obtain maximum yield less 0.25t; this last increment is less economic and less reliable to obtain.

Localised use of IN + 2 ΔN value to predict response.

In an area with common potential yield (Yp), the procedure can be simplified by expressing N requirements simply as a function of Yp and the IN + 2 ΔN value.

Climate-induced between-year variation in yield — effects on N response and use of procedure

In presence of adequate moisture. Wheat yields in a given area are known to vary markedly from year to year. Crops with identical paddock history and fertility, and adequate moisture, can vary in yield in extreme cases by as much as 3t/ha due to climatic variation between years, as shown under irrigation at Winchmore (Table 7). This is no doubt the reason for much of the variability in Fig. 1.

Nevertheless, the slope of the N response remained relatively constant, as does the maximum increase in yield obtainable with N (Table 7).

The similar N response slopes reflect the fact that much of the between-year variation in yields is a direct or indirect function of variation in N availability, through changes in NO_3-N leaching (winter rainfall effect) and mineralisation of soil organic N (soil temperature effect). The similar maximum increase in yield obtainable with N indicates that the same climatic variables that are affecting

TABLE 7: Comparison of 1980/81 and 1981/82 yields and N response for irrigated wheat crops with identical paddock history and fertility status.

	Yield (no N applied) (t/ha)	Efficiency of response (kg N/tonne increase in yield)	Max. increase in yield (t/ha)	Grain N uptake (no N applied) (kg N/ha)
1980/81	5.7	37	1.3	124
1981/82	2.9	40	1.2	67

mineralisation of organic N (e.g. temperature) are also affecting plant physiological processes. In other words, although a certain increase in yield is obtainable with N, climatic variables will impose the absolute ceiling on yield in a given year.

Because the N response slopes and absolute yield increases are relatively constant between years (given adequate moisture), the procedure for calculating the optimum N requirement as described should be largely independent of climatic variations between years. Steele *et al.* (1982) came to the same conclusion for maize. Therefore there will be less error in the optimum N recommendation than the variability in Fig. 1 would suggest.

Under severe moisture stress. In areas prone to severe and unpredictable moisture stress at critical stages of crop development, for example the shallower (non-irrigated) soils of Mid and South Canterbury, the procedure will naturally be less reliable. In these situations, the N application should be reduced to 50% of that calculated for the procedure to avoid the risk of a N-induced suppression of yield during periods of moisture stress.

Use of the procedure in other times of the year

Autumn and Winter. Although this procedure for calculating optimum N requirements for wheat has been designed primarily for use in late winter/early spring, it can be useful to assess the N fertility status of paddocks under autumn-sown crops earlier in the year. For example, early-sown crops may benefit from a small application of "starter N" if mineral N values are low.

If IN + 2ΔN is determined in autumn or winter, the necessity to retest IN in late winter/early spring (ΔN will not have changed significantly) can be avoided by adding 0.25 μg/g per day from the date of the test until August 31, multiplied by [50 ÷ 50 + (total rainfall (mm)] - no of days) for the same period. (If the total rainfall is less than the number of days, use zero).

Example: IN value 3 May was 7. Rainfall to 31 August was 270 mm. Therefore:

$$\text{IN (31 August)} = 7 + \left[(120 \times 0.25) \times \frac{50}{50 + (270-120)}\right] = 14\ \mu g/g$$

This method is based on the assumptions (i) mineralisation rates are low in the winter months (average 0.25 μg/g/day) and vary little between paddocks at these temperatures; (ii) available soil moisture in the top 15 cm is approximately 50 mm; (iii) evaporation in the winter months averages 1 mm/day; (iv) rainfall tends to mix with rather than displace soil water. Although very approximate, the method is justified by the relatively small contribution to the N recommendation made by IN compared to ΔN.

Late Spring. To use the procedure later in spring it is necessary only to reduce the estimate of N required by the amount of N (in kgN/ha) already present in the above-ground crop. This can be measured (e.g. from 1m^2 plots) or estimated from available data on N uptake during the growth of the crop (Quin and Drewitt, 1979).

Extension of procedure to other crops

The procedure can be used for other crops provided the relationship between yield and IN + 2ΔN and the kg product/kgN ratio are determined. The limited information available suggests that the procedure as described for wheat can be used without alteration for barley.

CONCLUSIONS

Nitrogen fertiliser recommendations for wheat crops have traditionally been very imprecise because of lack of suitable soil test to assess N fertility status, and complications due to variations in winter leaching of soil NO_3-N, the availability of moisture during the growth of the crop, the wide range of soil types, depths and potential yields in wheat-growing areas and the differences in potential yields and N responses between cultivars.

In this study, the yield of wheat in the absence of applied fertiliser but in the presence of adequate moisture and other nutrients (Yo) was related to a combination of the initial mineral N (IN) and the increase in mineral N on incubation for 7 days at 37 °C (ΔN). The combination IN + 2ΔN gave the best relationship, and the 0-15 cm soil depth was superior to deeper depths.

The maximum yield obtainable where N is non-limiting (Yp) can be derived from local research trials and recorded yield for districts or individual farms.

The N required to obtain Yp is calculated by multiplying Yp-Yp (in t/ha) by 40 (Canterbury) or 50 (Otago, Southland).

Climate-induced between-year variations in yield (except those caused by severe moisture stress) do not appear to affect the validity of the procedure. As the use of shallow (particularly if non-irrigated) soils for wheat cropping is declining, moisture stress is of less importance.

Although the proposed procedure could and should be refined as further data becomes available, it is concluded that it represents a considerable improvement over existing methods for the calculation of fertiliser N requirements for individual wheat crops (autumn and spring-sown) and is suitable for extension to use on other crops.

The disadvantage of the time required for the incubation (7 days) is more than made up for by the flexibility in the timing of the test and its reduced susceptibility to errors due to small changes in the mineral N content during storage of the sample prior to analysis.

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