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Soil Fertility and Plant Nutrition

Long-term Trends in Fertility of Soils Under Continuous Cultivation and Cereal Cropping in Southern Queensland. VIII* Available Nitrogen Indices and their Relationships to Crop Yield and N Uptake

R. C. Dalal and R. J. Mayer

Queensland Wheat Research Institute,
Department of Primary Industries, Toowoomba, Qld 4350.

Abstract

Six major soil series of southern Queensland were studied for the changes in the levels of available N indices (determined by both biological and chemical methods) and nitrate-N, with continuous cultivation and cereal cropping for up to 70 years. The biological N indices, measured in soil collected at planting of winter cereals, were anaerobic mineralizable N, aerobic mineralizable N and nitrate-N down to 1·2 m depth. The chemical indices were autoclave N and oven N. The predictive capabilities of various available N indices, and total N and organic C, were assessed from dry matter and N uptake of winter cereals in the field in 1983 as well as in the glasshouse.

Anaerobic mineralizable N levels increased with mean annual rainfall but decreased with mean annual temperatures of the sampling sites of the six soil series. Therefore, it was possible to predict closely anaerobic mineralizable N from soil total N, and mean annual rainfall and temperature. Autoclave N showed no such trends.

Anaerobic mineralizable N declined with period of cultivation, exponentially in Waco, Langlands–Logie and Cecilvale soils (0·112, 0·111 and 0·247 year^{-1}, respectively) and linearly in the other three soil series. No consistent trends were discerned in autoclave N and oven N in four of the soil series with period of cultivation. Generally, nitrate-N (measured at planting) declined with period of cultivation. However, in Billa Billa soil, it increased in the soil profile (0–1·2 m) during the initial 7 years of cultivation and declined rapidly after 12 years.

Although a number of available N indices, including total N and organic C, were significantly correlated with crop dry matter yield and N uptake, the best prediction of crop performance was provided by a combination of anaerobic mineralizable N (0–0·3 m) and nitrate-N (0–0·6 m) in the six soil series.

Introduction

Continuous cultivation and cereal cropping generally leads to reduced organic matter level in soil (Haas *et al.* 1957). The loss of nutrient-supplying capacity, especially nitrogen, could even be proportionally greater than the loss of total organic matter. For example, Campbell and Souster (1982) found that loss of potentially mineralizable N, a measure of nitrogen-supplying capacity of soil, was greater than that of organic C or total N upon cropping of chernozemic soils. Dalal and Mayer (1987*b*) found that, for most southern Queensland soils, nitrogen mineralization potential (Stanford and Smith 1972) did not provide a significantly more sensitive index of soil fertility degradation due

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to cultivation than that shown by total soil N loss. The overall decline in anaerobic mineralizable N, a biological index of available N (Keeney 1982), however, was proportionally much larger than that of organic C or total N in these soils after 20–70 years of cultivation for cereal cropping (Dalal and Mayer 1986*a*). Other available N indices include aerobic mineralizable N, autoclave N (chemical index) and nitrate-N (Keeney 1982). Therefore, the objective of the present study was to compare the rates of loss in available N indices in six soil series due to cultivation and cropping for up to 70 years in southern Queensland. These indices were then compared with particle-size and light C and N fractions, and total N and organic C (Dalal and Mayer 1986*b*, 1986*c*, 1987*a* and 1987*b*) for their ability to predict responses in cereal crops, grown in the glasshouse as well as in the field.

Materials and Methods

The study area (between 27° and 30°S. and 148° and 152°E.), description of soils, cultural practices, and soil sampling and analytical techniques were described by Dalal and Mayer (1986*a*). The number of sampling sites of virgin and adjacent cultivated soils, respectively, were 5 and 16 in Waco soil series, 6 and 12 in Langlands–Logie soil series, 7 and 12 in Cecilvale soil series, 7 and 14 in Billa Billa soil series, 6 and 16 in Thallon soil series and 5 and 13 in Riverview soil series. The overall ranges in pH values, clay and organic C contents of the six soil series (0–0·1 m depth) from virgin sites were 6·5–8·1, 19–74% and 0·77–2·23%, respectively.

Available Nitrogen Indices

Biological indices

Anaerobic mineralizable N. The amount of NH_4^+-N produced in soil incubated under waterlogged conditions (Waring and Bremner 1964) at 40°C for 7 days was measured to provide a biological index of available N (Keeney 1982). Briefly, 5 g of soil, previously dried at 25°C and ground to <2 mm, was carefully poured into a tube (16 by 150 mm) containing 12·5 ml of deionized H_2O. The tube was stoppered and the submerged soil was incubated at 40°C for 7 days. Then the contents were transferred to a 100 ml glass bottle by using three 12·5 ml volumes of 2·67 M KCl, shaken for 1 h, filtered through Whatman No. 40 filter paper and the NH_4^+-N in the filtrate was determined spectrophotometrically (Crooke and Simpson 1971). The amount of NH_4^+-N present in the pre-incubated samples, usually <2 mg kg^{-1} soil, was subtracted from that in the incubated soil to estimate anaerobic mineralizable N.

Aerobic mineralizable N. Aerobic mineralizable N in soil was measured by the modified procedure of Stanford and Smith (1972) by incubating samples at 40°C for 2, 4, 8, 12, 16, 22 and 30 weeks, as previously described (Dalal and Mayer 1987*b*). Since the amount of aerobic mineralizable N produced during the first 2 weeks of incubation may have been influenced by air-drying (Standford and Smith 1972), the mineral N produced after 4 weeks of incubation was taken as aerobic mineralizable N.

Chemical Indices

Autoclave N

The amount of NH_4^+-N produced by soil suspended in a solution of 0·01 M $CaCl_2$ and autoclaved at 121°C for 16 h provided a chemical index of available N (Keeney 1982). Briefly, 5 g of air-dried soil, ground to <2 mm, was placed in a 28 ml McCartney bottle, 12·5 ml of 0·01 M $CaCl_2$ solution was added and the contents were gently mixed. The bottle was stoppered and autoclaved for 16 h at 121°C and 101 kPa pressure. After allowing the contents to cool to room temperature, 37·5 ml of 2·67 M KCl was added, and the mixture was shaken for 1 h. The contents of the bottle were then filtered and NH_4^+-N was measured in the filtrate, as for anaerobic mineralizable N.

Oven N

This fraction was estimated as the amount of NH_4^+-N produced when 3 g of air-dried, <2 mm soil and 20 ml of 2 M KCl were heated in a stoppered McCartney bottle in an oven at 100°C for 4 h (Gianello and Bremner 1986). After allowing the contents to cool to room temperature, 10 ml of 2 M KCl was added and the mixture was shaken for 1 h. The contents were filtered through a Whatman No. 40 paper, and NH_4^+-N in the filtrate was determined as before.

NO_3^--N and total N

Nitrate-N in soil was measured in 2 M KCl extracts (Best 1976) and total N in soil was determined by the Kjeldahl method, modified to include NO_3^--N (Dalal *et al.* 1984*b*).

All availability indices, except aerobic mineralizable N, were estimated in soil samples collected from 0–0·1, 0·1–0·2, 0·2–0·3, 0·3–0·6, 0·6–0·9 and 0·9–1·2 m layers. These were calculated on an oven-dry weight basis. Using bulk density and equivalent soil weight–soil depth relationships (Dalal and Mayer 1986*b*), N values were calculated on a soil volume basis. Aerobic mineralizable N was estimated in soil samples collected from the 0–0·1 m layer only.

Crop Yields and Nitrogen Uptake

Glasshouse experiment

Wheat (*Triticum aestivum* L., cv. Hartog), four plants in each pot, was grown for 80 days in 0·15 m diameter plastic-lined pots, each containing a similar volume of soil (1·5–2·5 kg air-dried soil). Soil water was adjusted to field capacity regularly. The soil samples collected from 0–0·1, 0·1–0·2 and 0·2–0·3 m layers only were used to estimate dry matter yields and N uptake.

Field experiment

The dry matter and grain yields and N uptake by winter crops were measured in 1983 when winter rainfall, April–September inclusive, was approximately twice the mean for the study area. For example, in Dalby, Queensland, one of the study areas, 490 mm of rainfall was received during this period against mean winter rainfall of 223 mm. Plant samples of winter crops, mainly wheat and barley, were collected from cultivated areas where soil samples had been obtained, by harvesting 10 quadrats (0·5 m^2 each) at maturity. Dry matter yields were obtained by drying the plant samples at 80°C for 24–48 h. Grain and straw were then separated, weighed, ground to pass a 1 mm sieve and stored in sealed plastic containers.

Plant samples from both glasshouse and field experiments were analysed for N by digesting the samples in concentrated H_2SO_4 containing K_2SO_4, $CuSO_4.5H_2O$, and magnesium stearate, then determining NH_4^+-N in the acid digest by the spectrophotometric method of Crooke and Simpson (1971).

Statistical Analysis

Available N indices were corrected for changes in bulk density with the period of cultivation (Dalal and Mayer 1986*b*), and the trends with period of cultivation were estimated using exponential regression when regression coefficients were significant at $P < 0·05$ (Draper and Smith 1966), otherwise alternative linear or quadratic regression models were used.

Dry matter yield and N uptake in the pot experiment were regressed against available N indices and organic C using Mitscherlich, linear or quadratic equations, provided that the regression coefficients were significant. The field dry matter yield, grain yield and total N uptake (after adjusting for site differences via covariates) were similarly related to available N indices (which were 'estimated' for the appropriate period of cultivation whenever the field yields were measured one year or more after soil sampling).

Results

Available Nitrogen Indices in Virgin Soils

The amounts of anaerobic mineralizable N varied by as much as five times in 0–0·1 m soil layers and by ten times in the 0–1·2 m layers, among the six soil series, whereas autoclave N varied by only about two times throughout the profiles of these soils (Table 1). The proportion of total N as nitrate-N varied from 0·1% in the Cecilvale clay soils to 0·5% in Billa Billa loamy clays. Anaerobic mineralizable N as a proportion of total N was least in the Riverview sandy loams (3·2%) and it generally declined with depth in all soils, whereas the proportion of autoclave N differed much less among soils (5·5–8·3%) and it either remained similar (Waco) or increased with depth. Distribution of oven N was similar to that of autoclave N, although it comprised a much smaller proportion of total N (1·0–2·5%) than the latter (5·9–9·0%).

Table 1. Amounts of anaerobic mineralizable N and autoclave N in the 0–0·1, 0–0·3 and 0–1·2 m soil layers

Mean±s.d. values from virgin sites

Soil series (No. of sites)	Anaerobic mineralizable N ($kg\ ha^{-1}$) 0–0·1 m	0–0·3 m	0–1·2 m	Autoclave N ($kg\ ha^{-1}$) 0–0·1 m	0–0·3 m	0–1·2 m
Waco clay (5)[A]	105±20	228±19	432±14	73±6	172±10	459±24
Langlands-Logie clay (6)[B]	119±9	258±29	410±34	108±4	273±7	797±22
Cecilvale clay (7)[B]	99±8	207±28	325±43	82±6	193±12	466±47
Billa Billa loamy clay (7)[B]	61±10	137±18	212±15	85±8	219±36	564±124
Thallon clay (6)[B]	23±6	60±15	135±18	51±8	168±20	517±29
Riverview sandy loam (5)[C]	33±8	40±8	44±10	66±6	169±22	416±88

[A] Typic Pellusterts. [B] Typic Chromusterts. [C] Rhodic Paleustalfs.

Over the six soil series, anaerobic mineralizable N was significantly correlated with mean annual rainfall ($r = 0 \cdot 85^*$) and temperature ($r = -0 \cdot 86^*$), similar to that observed for total N (Dalal and Mayer 1986*c*). The effect of temperature on anaerobic mineralizable N, however, was greater than that observed on total N, so that anaerobic mineralizable N as a proportion of total N declined with increasing mean annual temperature ($r = -0 \cdot 97^{**}$). Autoclave N, oven N and nitrate-N were not significantly correlated with either mean annual temperature or rainfall.

Changes in Available Nitrogen Indices in Cultivated Soils

The relationships between available N indices (Y) and period of cultivation (t) were described according to the exponential equation

$$Y_t = Y_e + (Y_0 - Y_e)\exp(-kt), \tag{1}$$

where Y represents the index at time zero (Y_0), at time t (Y_t) or at equilibrium (Y_e) and k is the rate of loss, $year^{-1}$ (Fig. 1). The rates of loss (k values) in anaerobic mineralizable N, aerobic mineralizable N and autoclave N with increasing period of cultivation of Waco soil were 0·112±0·037, 0·208±0·092 and 0·056±0·026 year^{-1}; the respective half-lives ($t_{1/2} = \ln 2/k$) were 6·2±2·1, 3·3±1·2 and 12·5±5·9 years, respectively.

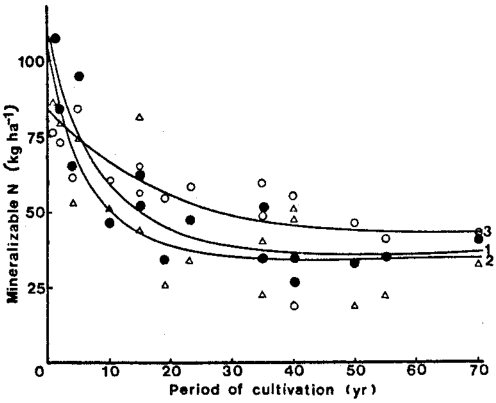

Fig. 1. Mineralizable N in relation to period of cultivation (t) in 0–0·1 m depth of Waco soil, for: 1. anaerobic mineralizable N, Y_1, (○); 2. aerobic mineralizable N, Y_2, (●); 3. autoclave N, Y_3, (△). The relevant equations are

1. $Y_1 = 37^{**} + 69^{**}$; $\exp(-0{\cdot}112^{**}t)$, $n = 21$, $R^2 = 0{\cdot}84$;
2. $Y_2 = 35^{**} + 68^{**}$; $\exp(-0{\cdot}208^{*}t)$, $n = 21$, $R^2 = 0{\cdot}77$;
3. $Y_3 = 41^{**} + 43^{**}$; $\exp(-0{\cdot}056^{*}t)$, $n = 21$, $R^2 = 0{\cdot}76$.

Table 2. Initial values (Y_0), equilibrium values (Y_e), rate of loss (k) and half-life ($t_{1/2}$) of anaerobic mineralizable N at different depths in three soils

Mean±s.e. values are given

Soil series[A]	Soil depth (m)	Y_0[B] (kg N ha^{-1})	Y_e[B] (kg N ha^{-1})	k[B] (year^{-1})	$t_{1/2}$[B] (year)	R^2
Waco	0–0·1	106±5	37±5	0·112±0·037	6·2±2·1	0·84
	0–0·2	185±8	63±9	0·093±0·026	7·5±3·0	0·88
	0–0·3	233±8	89±11	0·075±0·020	9·2±2·4	0·90
	0–0·6	342±11	151±29	0·042±0·016	16·4±6·0	0·87
Langlands–Logie	0–0·1	117±3	47±5	0·111±0·025	6·2±1·4	0·93
	0–0·2	203±8	114±11	0·135±0·058	5·1±2·2	0·79
	0–0·3	261±10	159±13	0·158±0·075	4·4±2·1	0·78
Cecilvale	0–0·1	100±3	46±3	0·247±0·073	2·8±0·8	0·93
	0–0·2	162±6	84±7	0·194±0·082	3·6±1·5	0·84

[A] Waco, Langlands–Logie and Cecilvale soils have been cultivated for 0–70, 0–45 and 0–35 years, respectively.
[B] Y_0, Y_e and k were calculated according to equation (1), $t_{1/2} = \ln 2/k$.

Significant rates of decline of anaerobic mineralizable N occurred up to 0·6 m depth in the Waco soils, 0·3 m depth in the Langlands–Logie soils and 0·2 m depth in the Cecilvale soils (Table 2). In the Waco and Cecilvale soils, the k values decreased with depth, whereas those in the Langlands–Logie soils were essentially similar at different depths.

The exponential equation (1) did not apply [that is, the regression coefficients were not significantly different from zero at $P<0\cdot05$ (Draper and Smith 1966)] to the changes in available N indices with period of cultivation in Billa Billa, Thallon and Riverview soils, and to those of oven N and NO_3^--N in all soil layers as well as to all available N indices in deeper layers of all soils. In these cases, linear ($Y_t = Y_0+a_1 t$) or quadratic ($Y_t = Y_0+a_1 t+a_2 t^2$) equations were used, where a_1 and a_2 are regression coefficients.

Anaerobic mineralizable N declined (only $R^2 \geq 0\cdot5$ values are considered) at the rate of 3·65±0·38, 3·34±0·69, 2·73±0·61, 2·24±0·58 and 0·93±0·20 kg ha^{-1} yr^{-1} in Waco (0–1·2 m), Langlands–Logie (0–1·2 m), Cecilvale (0–0·3 m), Billa Billa (0–0·3 m) and Thallon (0–0·2 m) soils, respectively. No trend could be discerned for autoclave N or oven N in these soils, except in Riverview soil where oven N declined at the rate of 1·39±0·29 kg ha^{-1} yr^{-1} (0–0·3 m).

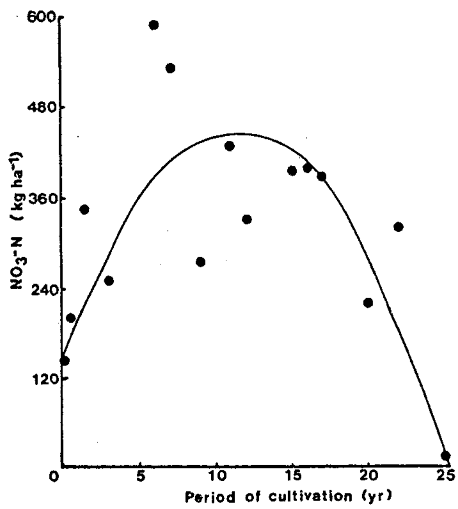

Fig. 2. Nitrate-N (Y) in 0–1·2 m depth of Billa Billa soil in relation to period of cultivation (t). The relevant equation is

$$Y = 146\cdot8+53\cdot3^{**}t-2\cdot3^{**}t^2, \quad R^2 = 0\cdot62.$$

Nitrate-N content in Waco and Langlands–Logie soils showed no trend with the period of cultivation. However, it declined up to 1·2 m depth from Riverview (5·9±1·2 kg ha^{-1} 1·2 m^{-1} yr^{-1}) and up to 0·2 m depth from Thallon soils (0·4±0·1 kg ha^{-1} 0·2 m^{-1} yr^{-1}). On the other hand, in Billa Billa soils, it increased in the soil profile (0–1·2 m depth), mostly at 0·6–1·2 m depth, for the first 7 years, then declined to a low level after 25 years of cultivation (Fig. 2).

Crop Yields and Nitrogen Uptake

Pot experiment

Dry matter yields were closely correlated with N uptake at the three depths studied in six soil series ($r = 0\cdot93^{**}$, $n = 357$).Nitrogen uptake from plants grown

Table 3. Anaerobic mineralizable N and total nitrogen levels required for 90% of maximum yield

Plant parameters	Anaerobic min. N (kg ha^{-1}) 0–0·1 m	0–0·3 m	Total N (kg ha^{-1}) 0–0·1 m
	Field experiment (n = 39)		
Dry matter yield	47 (0·61)[A]	151 (0·84)[A]	1045 (0·68)[A]
Grain yield	74 (0·47)[B]	152 (0·64)[B]	1056 (0·59)[A]
Total N uptake	75 (0·60)[B]	156 (0·77)[B]	1196 (0·65)[B]
	Pot experiment (n = 119)		
Dry matter yield	94 (0·47)[B]	169 (0·48)[B]	1582 (0·50)[B]
Total N uptake	82 (0·62)[B]	166 (0·62)[B]	1535 (0·59)[B]

[A] Values in parentheses are the R^2 values obtained between plant parameters (y) and anaerobic mineralizable N or total N (x) from the exponential relationship $y = b_0 - b_1 \exp(-cx)$, where b_0 is maximum yield, and b_1 and c are constants.
[B] R^2 values obtained from the quadratic relationship $y = ax^2+bx+c$, where a and b are constants; when y is maximum, $x = -b/2a$.

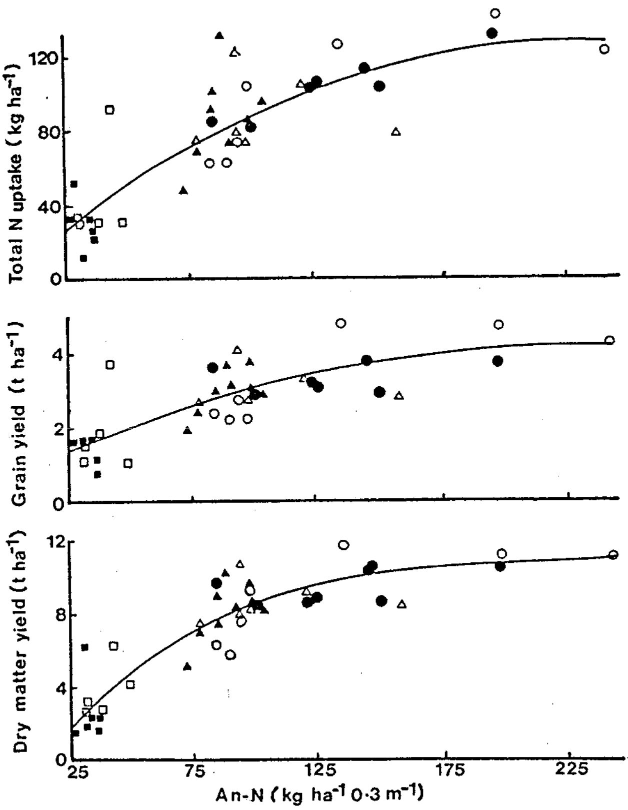

Fig. 3. Relationship between anaerobic mineralizable N (An-N) (x) and dry matter yield (DM), grain yield (GY) and total N uptake (NU). Symbols represent Waco (○), Langlands–Logie (●), Cecilvale (△), Billa Billa (▲), Thallon (□) and Riverview (■). The relevant equations are

$$DM = 11 \cdot 2^{**} - 14 \cdot 2^{**} \exp(-0 \cdot 01688^{**} x), \quad R^2 = 0 \cdot 84,$$

$$GY = 0 \cdot 63 + 0 \cdot 03^{**} x - (6 \cdot 7 \times 10^{-5**}) x^2, \quad R^2 = 0 \cdot 64,$$

$$NU = -0 \cdot 97 + 1 \cdot 14^{**} x - 0 \cdot 0025^{**} x^2, \quad R^2 = 0 \cdot 77.$$

in the top $0 \cdot 1$ m soil from the virgin sites was in the order (mg N kg^{-1} soil): Waco $(44 \cdot 6) >$ Billa Billa $(39 \cdot 7) >$ Langlands–Logie $(37 \cdot 6) >$ Cecilvale $(28 \cdot 0) >$ Thallon $(13 \cdot 5) >$ Riverview $(10 \cdot 7)$. This trend was generally followed at $0 \cdot 1$–$0 \cdot 2$ m and $0 \cdot 2$–$0 \cdot 3$ m depths except that N uptake from Billa Billa soil at these two depths exceeded those from Waco and Langlands–Logie soils.

Plant N uptake from the top $0 \cdot 1$ m layer of all six soil series declined significantly upon cultivation (from 11% in Thallon soils to 37% in Billa Billa soils). Langlands–Logie and Billa Billa soils showed a greater decline in N uptake than other soils, not only from the top $0 \cdot 1$ m depth but also from $0 \cdot 1$–$0 \cdot 2$ m and $0 \cdot 2$–$0 \cdot 3$ m depths.

Correlation coefficients between plant N uptake in the glasshouse experiment and available N indices, other soil N fractions (Dalal and Mayer 1986*c*, 1986*d*) and organic C, resulted in the following order of r values (in parentheses) for $n = 119$, 0–$0 \cdot 1$ m depth of all soils: anaerobic mineralizable N $(0 \cdot 74) >$ total N $(0 \cdot 72) >$ aerobic mineralizable N $(0 \cdot 68) >$ clay N $(0 \cdot 68) >$ organic C $(0 \cdot 66) >$ sand N $(0 \cdot 58) >$ N mineralization potential, N_0, $(0 \cdot 55) >$ autoclave N $(0 \cdot 54) >$ oven N $(0 \cdot 54) >$ microbial biomass-N $(0 \cdot 52) >$ NO_3^--N $(0 \cdot 50)$.

The prediction of plant N uptake from anaerobic mineralizable N and total N improved significantly when NO_3^--N was considered together with available N indices ($n = 119$):

$$\text{Plant N} = 1 \cdot 8 + 0 \cdot 48^{*}NO_3^-\text{-N} + 0 \cdot 48^{**}\text{An-N}16 \times 10^{-4**}(\text{An-N})^2, \qquad (2)$$

$$\text{s.e. estimate} = 6 \cdot 1, \quad R^2 = 0 \cdot 79;$$

$$\text{Plant N} = -11 \cdot 4 + 0 \cdot 46^{*}NO_3^-\text{-N} + 42 \cdot 0^{**}\text{TN} - 85 \cdot 2^{**}(\text{TN})^2, \qquad (3)$$

$$\text{s.e. estimate} = 6 \cdot 7, \quad R^2 = 0 \cdot 75;$$

where plant N, anaerobic mineralizable N (An-N) and NO_3^--N are expressed in mg kg^{-1} soil, and total N (TN) is in g kg^{-1} soil (0–$0 \cdot 1$ m depth).

Anaerobic mineralizable N and total N required for 90% of maximum yield were essentially similar for both dry matter yield and total N uptake (Table 3).

Field experiment

Among all the available N indices, only anaerobic mineralizable N, aerobic mineralizable N and total N were significantly related to the 'site' adjusted dry matter, grain yield and total N uptake (Fig. 3 and Table 3). The association between the yield and anaerobic mineralizable N improved as the soil depth for the latter increased (Table 3); the reverse was the case for total N. Prediction of dry matter yield improved significantly when NO_3^--N at 0–$0 \cdot 6$ m was included along with anaerobic mineralizable N:

$$DM = -1093 + 121^{**}\text{An-N} - 0 \cdot 31^{**}(\text{An-N})^2 + 0 \cdot 10^{*}(NO_3^-\text{-N})^2, \qquad (4)$$

$$\text{s.e. estimate} = 1507, \quad R^2 = 0 \cdot 86,$$

where DM is field dry matter yield (kg ha^{-1}), An-N is anaerobic mineralizable N and NO_3^--N (kg ha^{-1}) in soil.

Anaerobic mineralizable N and total N required for 90% maximum yield were generally lower for field dry matter yield than total N uptake or grain yield (Table 3).

Discussion

Available Nitrogen Indices

The available N indices considered in this study, although significantly correlated with each other, as in other studies (Smith and Stanford 1971), exhibited different rates of change with period of cultivation (Table 4). For example, in Waco soil, rates of loss of anaerobic and aerobic mineralizable N were 2–3 times greater than that of autoclave N, but closer to those of nitrogen mineralization potential, clay-size N, sand-size C and light fraction N. The rate of loss of autoclave N (0·056 yr^{-1}) was essentially similar to that of total N (0·061 yr^{-1}) and organic C (0·065 yr^{-1}). However, in Langlands–Logie soil, the rates of loss of anaerobic mineralizable N, aerobic mineralizable N and autoclave N were essentially similar to that of total N. Therefore, it is unlikely that any one of the available N indices would reflect similarly the mineralizability or lability of organic N in a wide range of soils.

Table 4. Comparison of exponential rates of loss of mineralizable N with that of organic C and N from different fractions in three soil series (0–0·1 m), expressed on w/v basis

Fraction	Rate of loss (yr^{-1})					
	Waco		Langlands–Logie		Cecilvale	
	N	C	N	C	N	C
			Mineralizable N			
Anaerobic N	0·112		0·111		0·247	
Aerobic N	0·208[F]		n.s.[G]		0·193[F]	
Autoclave N	0·056		0·131		0·339	
Mineralization potential	0·091[F]		0·078[F]		n.s.	
Microbial biomass-N	n.s.		0·101[F]		n.s.	
			Particle-size N and C			
Sand	n.s.	0·096[B]	0·131[E]	0·109[B]	n.s.	0·166[B]
Silt	n.s.	0·039[B]	0·109[E]	0·078[B]	n.s.	0·237[B]
Clay	0·103[E]	0·057[B]	n.s.	0·039[B]	n.s.	0·062[B]
			Density-size N and C			
Light fraction (<2 Mg m^{-3})	0·188[E]	0·365[C]	0·183[E]	0·194[C]	0·482[E]	0·293[C]
Heavy fraction (>2 Mg m^{-3})	0·053[E]	0·033[C]	0·101[E]	0·026[C]	0·237[E]	0·143[C]
			Whole soil N and C			
	0·061[D]	0·065[A]	0·115[D]	0·080[A]	0·275[D]	0·180[A]

[A] Dalal and Mayer (1986*b*). [B] Dalal and Mayer (1986*c*). [C] Dalal and Mayer (1986*d*). [D] Dalal and Mayer (1986*e*). [E] Dalal and Mayer (1987*a*). [F] Dalal and Mayer (1987*b*). [G] n.s., not significant.

Oven N values were poorly correlated with the period of cultivation in most soils and with other available N indices, although Gianello and Bremner (1986) reported that oven N values were closely correlated with anaerobic and aerobic mineralizable N in 30 Iowa soils.

Nitrate-N contents in these soils were generally measured at the end of the summer fallow period which is at the time of planting of winter cereals.

Therefore, this N index should have reflected the N mineralization rates during the fallow and, hence, the effect of period of cultivation in these soils. This was so in Thallon and Riverview soils where mineralizable (anaerobic) N levels were the lowest (Table 1) and N mineralized during fallow was probably utilized by the succeeding crop. In other soils, especially Langlands–Logie and Billa Billa soils, the amount of N mineralized exceeded crop N uptake in a few initial years of cultivation and thus nitrate-N accumulated in the soil profile (Billa Billa, Fig. 2) and/or leached beyond the root zone or below 1·2 m depth (Langlands-Logie; R. C. Dalal, unpublished data). Dalal (1984*a*) reported that, in Billa Billa soil, NO_3^--N accumulated at the rate of 29 kg N ha^{-1} $year^{-1}$ at 0·6–1·2 m depth in the first 7–12 years of cultivation. After 7–12 years of cultivation and cropping of these soils, accumulated NO_3^--N in the soil profile declined (Fig. 2), probably because crop N uptake either exceeded mineralized N and/or accumulated NO_3^--N leached beyond the root zone (Wetselaar and Norman 1960; Waring and Teakle 1960; Catchpoole 1987).

Dry Matter Yield and Nitrogen Uptake in Relation to Available Nitrogen Indices

It was found necessary to adjust the dry matter and grain yields and N uptake for 'site' or 'soil series' differences (via covariate variables) to improve the relationship with the available N indices. This was not required for the yield data from the glasshouse experiment because of the uniform environmental conditions (temperature, moisture) for plants grown in different soils. Relationships between field dry matter yields to available N indices, although similar within a soil series, differed significantly among soil series, mainly because of environmental differences among the soil series (Dalal and Mayer 1986*a*). Moisture conditions were probably only marginally, if at all, limiting to crop growth in 1983. Temperature differences among the six soil series were probably important since temperature affects both crop growth and N mineralization. For example, mean monthly temperatures for October were 19·8°C for Dalby (Waco and Cecilvale soil series) and 21·4°C for Surat (Riverview soil series). Dry matter yield and N uptake of wheat obtained in the glasshouse experiment and adjusted field dry matter and grain yields and N uptake were significantly correlated with anaerobic and aerobic mineralizable N and total N. Chalk and Waring (1970), Stanford (1982) and Sahrawat (1984) have obtained good correlations between plant N uptake in pots and a number of available N indices including total N and organic C. Organic C was compared with N availability indices in this study because it can be rapidly determined and it is closely correlated with total N contents of the six soil series studied (Dalal and Mayer 1986*e*). However, it predicted crop N uptake less precisely than anaerobic and aerobic mineralizable N and total N.

Inclusion of NO_3^--N with N availability indices improved the correlations with dry matter yield and N uptake considerably. This is to be expected, since N availability indices, anaerobic and aerobic mineralizable N, autoclave N and oven N were measured in soil samples collected at or just before planting the cereals. The best prediction of N uptake, both in the glasshouse experiment and field experiment, was obtained when anaerobic mineralizable N and NO_3^--N were considered together. For field N uptake, anaerobic mineralizable N down to 0·3 m depth and NO_3^--N down to 0·6 m depth were superior to other N availability indices. Nitrate-N down to 0·6 m depth has been extensively used in Canada (Soper *et al.* 1971) and the Darling Downs, Queensland, (Strong 1981) to predict N fertilizer requirements for cereals, although Onken and Sunderman (1972) and Taylor *et. al.* (1988) found no improvement in the prediction of grain yields when NO_3^--N concentrations below 0·3 m depths were considered. The usefulness of considering mineralizable N with NO_3^--N for predicting dry matter and grain yields and N uptake has been demonstrated by a number of workers (Geist *et al.* 1970; Campbell 1978). Geist (1977) also found that anaerobic mineralizable N predicted N uptake better than total N.

Table 5. Cultivation period before crop nitrogen uptake declined to 90% of the maximum uptake

Nitrogen availability index	Sampling depth (m)	Cultivation period at 90% of max. yield (years)[A] Waco	Langlands–Logie	Cecilvale
Anaerobic	0–0·1	5·3 (3·8)[B]	8·3 (6·2)	2·5 (1·6)
mineralizable N	0–0·3	10·2 (8·3)	–(16·9)	—
Total N	0–0·1	0·7 (0)	10·4 (4·4)	1·2 (0)

[A] Calculated from the values of available N indices estimated from the quadratic relationship between crop N uptake and N availability index (Table 3) and the exponential relationship between anaerobic mineralizable N and period of cultivation (Table 2) and between total N and period of cultivation (Table 4, Dalal and Mayer 1986*e*).
[B] Values in parentheses are derived from the glasshouse experiment.

Estimates of anaerobic mineralizable N and total N levels required for 90% of maximum dry matter yield varied between glasshouse and field experiments (Table 3). By assuming that crop total N uptake reflected soil N supply better than other crop parameters, the maximum periods of cultivation and cropping required for crop N uptake to decline to 90% of the maximum uptake were 2·5 (5·1, 0–2 m), 10·2 and 16·9 years for Cecilvale, Waco and Langlands–Logie soils, respectively (Table 5). Leslie and Hart (1967) also suggested that crop responses to added N were less likely to occur during the first 5–15 years of cultivation of central Darling Downs soils. It should be emphasized that these conclusions would be modified if crop growth is limited by soil water, which happens frequently in the semi-arid environment, or if crops and soil management practices are altered.

It is concluded that mineralizable N declined in all soils with the period of cultivation and, together with NO_3^--N at planting, reflected nitrogen supplying capacity of the soils better than other available N indices (autoclave N, oven N and total N) and organic C. Since anaerobic mineralizable N can usually be measured in a shorter period than aerobic mineralizable N and it requires less exacting experimental conditions (such as moisture and aeration) than the latter, anaerobic mineralizable N is preferred as an available N index of soil.

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