PREDICTION OF NITROGEN INPUTS FOR SUGAR BEET

An Evaluation of Soil Tests and Soil Management Criteria in Arable Soils

END OF PROJECT REPORT

ARMIS 4272

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SUMMARY

Currently, advice on nitrogen (N) use for tillage crops employs an index system based on crop management. However, there has not been a systematic evaluation of several of its components or of the relevance of soil tests, alone or in conjunction. The objective of the current study, therefore, was to evaluate relevant soil management data, various biological and chemical soil tests, and measurements of Nmin (NH_4 + NO_3) in the root profile, for prediction of fertiliser N requirements. The data used in the study were derived from a data bank of results of field and laboratory experiments for sugar beet.

The following topics were addressed: selection of regression models based on soil management criteria; sustainability of contribution of soil N reserves; limitations of soil tests for N; long-term trends in Nmin and biomass C; relationship of mineral-N flush with biomass C; relevance of Nmin with growing-season rainfall; implications of winter rainfall for residual effects and their justification within the current soil N index. The main results were as follows:

1. Nmin accumulated progressively in the 0-60 cm profile from a minimum of ***circa*** 75 kg N ha^{-1} in January to a maximum of 350-400 kg N ha^{-1} at the end of June in the more fertile of the soils used in this study.

2. The importance of sustainability of soil N supply was demonstrated. The mean trend value for end of June Nmin was 300 kg ha^{-1} after one year's tillage. After 3, 5, 10, 20 and 50 years, Nmin was 85%, 78%, 69%, 60%, and 47%, respectively, of the one year's value. Although Nmin declined with time, its prolonged decline reflected the release of substantial reserves of soil N to available forms even in the long term.

3. Biomass C - an indicator of biological activity and soil quality - declined somewhat more rapidly over time, to a calculated 37% of the initial value after 50 years. The flush of mineral N (Nflush) induced by fumigation - an estimate of microbial N - constituted ***circa*** 15% of biomass C.

4. The best estimate of optimum fertiliser-N requirement was a regression model that included the following terms: years in tillage, ratio of years in tillage/years in ley, rainfalls for April-June and July-September. When the three most extreme outliers of the 86 data points were excluded, the model R^2 increased from 33% to 42%, which is relatively high for field calibration studies. Although arbitrary, this result may both accommodate and point up the inevitability of some extreme variation encountered under field conditions.

5. Other ancillary variables such as soil type or soil texture, yield potential, date of sowing, temperature, solar radiation and fertiliser N use in ley were also evaluated, but were non-significant. These have been shown by others to have inconsistent effects. It has been noted, for example, that build up of soil organic N in ley depends on the annual input of organic matter, and is little affected by fertiliser N within the normal range.

6. Sensitivity testing of the model for a range of representative values indicated the wide variation in optimum N obtainable at constant years tillage. The range at 5 years tillage, for example, was 38-109 kg N ha^{-1} for varied combinations of the ratio term, mean rainfall, or rainfalls that deviated plus or minus 100 mm for the combined intervals. Such a wide range is consistent with that observed by others, and not unexpected in large-scale field experiments or farming practice.

7. The range in mean model optimum N was ***circa*** 20-170 kg ha^{-1}. This compares with current advice, derived from the same basic criteria, of 45, 80, 120 and 150 kg ha^{-1} for four index categories designated by an index system specific to the sugar beet data. The index system provides less flexibility, does not cater for extended continuous tillage and, generally, fixed index values may reflect limited calibration data.

8. The model N value was within +/- 30 kg ha^{-1} of the experimental optimum in 42% of cases, comparable to the corresponding 43% observed for the latest revision of UK arable recommendations.

9. Of the soil tests, Nmin (0-60 cm depth), biomass carbon, total N, organic C and $CaCl_2$-reflux were most consistently correlated with the optimum fertiliser N over a wide range of years. In all, 6 biological and 8 chemical soil tests were evaluated. Combinations of soil tests and management data did not improve R^2 values.

10. Nmin was superior to other soil tests, when combined with July-September rainfall, but inferior to the model derived from soil management criteria. The R^2 value ***versus*** the optimum N requirement was 22.5%, compared with a value of 14.4% based solely on Nmin. The Nmin combination, however, provided for some distinction on the basis of soils. The results indicated a reduced availability of end of June levels of Nmin with increasing levels of rainfall in the period of maximum crop uptake. Also, it was evident that medium texture soils required substantially less adjustment for rainfall than the other, generally lighter, soils where Nmin provided the estimate of N availability.

CONCLUSIONS

- The results confirmed the view that simplified, empirical, approaches are relevant in predicting N requirements, because of uncertainty about the practical application of soil tests. However, they supported other available evidence that the current N index may need to be revised.

- A relatively rapid rate of decline in both Nmin and biomass C, as indicators of sustainable soil N availability and biological activity, was observed in the early years in tillage. It was evident, however, that there was also a continued decline in both over the longer term, which defines the operative time-span of soil N supply from organic reserves that derive from long term leys.

- The effect of prolonged duration in ley was evident, consistent with other observations and with the observed distribution of Nmin. Others have suggested that the interval to establish a new equilibrium for soil N status would be at least 50 years following any change in practice between ley and arable farming, which also indicates a greater long term role than appears to be envisaged, currently, for the effects of leys.

- The relevance of growing-season rainfall for availability of soil and fertiliser N was also demonstrated. Given our high annual and winter rainfalls, the relatively dominant contribution of N mineralisation in spring, and the generally permeable nature of our arable soils, which cannot be described as nitrate retentive, it appears that it may be easy to overstate the impact of residual ammonium and nitrate from the previous crop for our soils and environment.

- The above observations do not substantiate some of the categories within the current index. More generally, calibrations of fertiliser requirements with predictive tests demonstrably need to be established on the basis of field trials that accommodate large numbers of soils and sites over a number of years. Often, the outcome of such trials, compared with single site experiments, is that only the most robust and dominant variables prove significant. Large-scale calibration trials are more reflective of practical situations, and, inevitably, some variables may be excluded that prove significant for a lesser mix of variables or for narrowly controlled conditions. A specific example in this study was the lack of relationship of the fertiliser N requirement with date of sowing, although it has been shown to relate significantly in single site experiments.

INTRODUCTION

Field crops obtain their nutrients mainly from combinations of soil reserves and fertiliser inputs. In the case of nitrogen (N), ***circa*** 98% of the soil reserve is in organic form of various degrees of complexity, and is made available by biological processes to different extents over different periods of time. Compared with most areas of Europe, arable soils in Ireland release large quantities of N from organic reserves to the available mineral N (Nmin) form as ammonium and nitrate. Possible reasons include our cool temperate climate, which is conducive to accumulation of soil organic matter and, more immediately, the practice of ley-arable rotations in mixed farming systems.

The range in the quantity of total soil N (kg ha^{-1}) in the 20 cm plough layer of our arable soils varies from about 5000 in loamy sands to 6500 in sandy loams and 8500 in loams. Typically, the quantity in the root profile to 60 cm depth is of the order of 15000 kg ha^{-1}. Although measurable changes in the total N content of soils are difficult to observe under field cropping, even where there is active release from the organic phase, chemical fractionation of soils has shown that significant changes are induced in identifiable fractions, specifically the amino acid and hexosamine fractions, over relatively short time spans (Herlihy and O'Keeffe, 1983).

The complexity of predicting soil N availability to crops is evidenced in the seasonal variations of mineral N and the mineralisation process (Herlihy, 1979), and in the dependence of estimates of mineralisation on the date of soil sampling (Bonde ***et al.,*** 1988; El-Haris ***et al.,*** 1983). The complexity is also exemplified by the fact that N is mineralised from several pools of different degrees of availability (Juma & Paul, 1984), that residual organic N from crop production, which is distributed in all organic forms, is more susceptible to mineralisation than native soil N (Smith ***et al.,*** 1978), and that the relative activity of bacteria, fungi and protozoa varies seasonally and in response to soil management (Badalucco ***et al.,*** 1992; Herlihy, 1973).

When temperature rises in spring and early summer, microbiological activity in soil results in the decomposition of organic N and the accumulation of Nmin in the root profile. Although precise estimates of the quantity released to available forms are limited by the complex nature of soil N and by possible losses from the root zone, there are numerous direct and indirect methods of measuring availability. Nonetheless, there is a great deal of uncertainty about their practical application in prediction of fertiliser N inputs for crops, because of variability imposed by interaction of weather, crop management and crop growth (Thicke ***et al***., 1993), and of the likely simultaneous and opposing N transformations of mineralisation, immobilisation and denitrificaction (Greenwood, 1986). As a result, recognition has arisen that simplified, empirical approaches are relevant in predicting N requirements (Dahnke and Johnson, 1990).

The most direct assessment of the available soil N is provided by measurement of Nmin in the root profile at an appropriate time in relation to crop uptake of N. The significance of the contribution of the soil N can be judged from the fact that response of sugar beet to fertiliser N typically varies from less than 10% to little more than 20% between the early stages of the tillage rotation and continuous tillage (Herlihy, 1992a). Generally, the soil component provides 80-90% of the N needs of the crop. Although the pattern with cereals is somewhat similar early in the rotation, the soil N contribution is only about 50% in continuous tillage. The distinction arises from the different N uptake sequences in relation to the accumulation of Nmin from soil reserves. This accumulation is well timed for the subsequent rapid growth of sugar beet, with the potential for 100% uptake by the crop. In contrast, the maximum rate of uptake by cereals occurs before the end of tillering, effectively limiting the use of Nmin.

The magnitude and range in the availability of N between soils has important consequences, and needs to be taken into account in optimising the total N requirement and, consequently, the prediction of the fertiliser N input. Estimation of the latter, therefore, depends on quantifying the availability of soil N for the duration of crop uptake. In terms of prediction of fertiliser N requirements, laboratory tests are expected to discriminate successfully between various components of soil organic N that differ in their potential and rate of mineralisation. Various transformations, however, influence the amount of available soil N and fertiliser N ultimately absorbed by the crop. These include mineralisation of organic N to Nmin, the reverse process of N immobilisation, and losses by leaching and denitrification. Nevertheless, biological and chemical soil tests have been a topic of research in many regions over a long duration, but even tests that apparently correlated well with crop response or N requirement have not always justified practical application. In many cases, alternative procedures, based on soil management, have been used to indirectly estimate soil N availability. Generally, this has resulted in the use of broad 3-4 category index-systems, which reflect the proximate basis of such systems.

Whatever the basis of determining the supply of N from soil reserves, other characteristics may affect its availability and the fertiliser N requirement. These may include soil texture, or soil type, rainfall, yield potential and sowing date (Birch ***et al.***, 1967; Needham 1984; van der

Paauw, 1968). The benefits of including such variables with an estimate of N availability in multi-component static models have been shown to have variable success in different circumstances (Greenwood 1986).

In practical terms, the assessment of tests of soil N availability requires correlation and calibration with agronomic data, such as the optimum fertiliser N input (Nopt), established from large-scale field experiments on a range of soils. The data used in this study were derived from a data bank of field experiments on the N, P and K requirements of sugar beet, which provided yield-response curves, estimates of fertiliser inputs and laboratory estimates of nutrient availability. Previous publications based on the data bank addressed various aspects of crop nutrition, soil chemistry, nutrient availability and effects of restrictions to fertiliser use imposed by environmental and economic constraints (Herlihy, 1989; Herlihy, 1992a, 1992b; Herlihy and Hegarty, 1994; Herlihy and O'Keeffe, 1983). The objective of the current study was to assess relevant soil management criteria, various biological and chemical soil tests, and measurements of Nmin in the root profile, in terms of re-evaluating and predicting fertiliser N requirements of sugar beet across a range of soils and of years of contrasting weather conditions.

EXPERIMENTAL

Field data, soils and soil management

The agronomic data were provided by the data bank of results from 114 field experiments conducted between 1978 and 1985, for which optimum fertiliser N (Nopt) and other agronomic criteria were available (Herlihy, 1992a). Four sites were excluded from the original databank, because they were either reclaimed soils or incomplete in terms of basic soil management data. The soil types, which were representative of those under cultivation for sugar beet in Ireland, comprised the Clonroche, Athy, Kellistown, and Elton series and soil association 15 (Herlihy, 1992b). Generally, soil tests and soil management data were available only for a sub-group of 86 sites for the years 1980-1985. For these, the following variables provided the basis for evaluating rotation effects and management-based criteria: number of years in tillage (YrsTill), number of years previously in ley (YrsLey) and whether grazed or cut in ley; also fertiliser N and organic N inputs and clover content when in ley. In the data presented below, FertN (a) refers to chemical fertiliser N, whereas FertN (b) also includes contributions from clover N and N from manure or slurry for relevant sites. Net N inputs of 15 kg ha^{-1} per 10 t ha^{-1} of slurry (Carton, 1999) and 9.4 kg ha^{-1} per 10 t ha^{-1} manure were assumed for the long-term effects on soil N from application to grassland in spring. The N contribution from a good clover sward was taken as 100 kg ha^{-1} at zero fertiliser N input (Murphy, 1999). For the purposes of this study, adjustment for the effect of fertiliser N (x) on the clover N contribution (y) was made on the basis: $y = 100e^{-0.0038x}$ (Herlihy, unpublished). This line of best fit was based on data derived from a number of sources (Crush ***et al.,*** 1982; Murphy, 1985; Murphy ***et al.***, 1986). For a poor clover sward, the N contribution was taken as 25 kg ha^{-1} at <100 kg ha^{-1} of fertiliser N and 0 at >100 kg ha^{-1} of fertiliser N (Murphy, 1999; Ryan, 1999).

Other, ancillary, data included soil type, sowing date, and, from adjacent meteorological stations, rainfall expressed as cumulative amounts for April-June (Rain A-J), April-September (Rain A-S) or July-September (Rain Jl-S), mean daily air temperature for April-June (Temp A-J) and mean daily solar radiation for July-September (SR Jl-S).

Biological soil tests

Biological tests of N availability or biological activity included:

(1) N mineralisation (DeltaN a) by the standard 14-day aerobic incubation procedure (Keeney & Bremner, 1967), but with incubation temperature of 25C.

(2) Cumulative N mineralisation in pre-leached soils (DeltaN b) incubated for 7, 14 or 21 days at 25C (Stanford & Smith 1972).

(3) Microbial biomass C (BiomC) by chloroform-fumigation and incubation (Jenkinson and Powlson, 1976) on the presumption that it served as a proxy for mineralisation of organic N.

(4) The pool of mineral N induced by chloroform-fumigation, followed by reinoculation and incubation for 10 days (Nfum).

(5) Mineral N-flush, i.e. Nfum values corrected for basal N mineralisation activity by parallel incubation of samples without fumigation for 0-10 (Nflush a) or 10-20 days (Nflush b) – which reflects the level of biomass N.

(6) Respiratory activity by CO_2 production (CO_2C).

Chemical soil tests

Chemical tests included:

(1) 60 minute refluxing with 0.01 M $CaCl_2$ (Stanford, 1968) with direct distillation, or with H_2SO_4 digestion prior to distillation (Keeney and Bremner, 1966).

(2) UV absorption of $NaHCO_3$ extract (Fox and Piekelek, 1978).

(3) $Ba(OH)_2$-extractable polysaccharide, expressed as glucose equivalents (Jenkinson, 1968).
(4) Refluxing with 1M KCl (Whitehead, 1981).
(5) EUF analyses for soluble N (EUF Nsol), organic N (EUF Norg) and a composite value for available soil N (EUF soil N) (Nemeth, 1982; Wiklicky, 1982). The EUF analyses were provided by the R and D Department of Greencore plc.
(6) NH_4-N + NO_3-N in root profile segments of 0-20 cm, 21-40 cm, and 41-60 cm, expressed as Nmin 0-60 cm.
(7) Total soil N (TotN).
(8) Soil organic carbon (OrgC).

Where relevant, soil analysis values were expressed as kg ha^{-1} on the basis of soil bulk density measurements for the sites of 1350, 1500 and 1600 kg m^{-3} for the 0-20, 21-40 and 41-60 cm depths, respectively (Burke, 1985). All soil tests (<2mm air-dry soil) were not performed in all years, because of the evolving nature of the experimental program and limitations on resources. A greater number of tests and of sample depths were evaluated in 1983, which involved a greater number of sites compared with other years. With the exception of Nmin, for which profiles were sampled in the period 20-28 June in various years, analyses were performed on samples taken in mid January-mid February to 0-20 cm and, occasionally, 21-40 cm depths.

RESULTS AND DISCUSSION

Distribution of soil tests and soil management criteria

Tables 1 and 2 provide summaries of the main variables available in the 1978-85 and 1983 databanks. These illustrate the mean values, the range between variables and, for the soil tests, the relative difference between tests and, occasionally, between sample depths. The soil tests included biological tests indirectly related to the mineralisation process, such as BiomC and CO_2C, and those related directly to the pool of mineralisable N, such as Nmin, DeltaN and Nflush. The range of chemical extractants included such diverse methods as $CaCl_2$-extractable amino N and polypeptide N, $Ba(OH)_2$-extractable polysaccharide, $NaHCO_3$-labile organic matter and EUF extraction of inorganic and amino N by electro-dialysis and ultra-filtration. The data for $CaCl_2$N refer to digested and distilled extracts, both here and subsequently. Generally, the data provided a wide range in the values of all variables, from 0 to 222 kg N ha^{-1} for the optimum fertiliser input, from 1 to 50 years tillage and from 94 to 445 kg N ha^{-1} for Nmin. The range in soil test values was widest for $Ba(OH)_2$-glucose, CO_2C, $CaCl_2$N and OrgC over the full range of years (Table1). More extensive data on sample depths and other aspects of soil N distribution, including the mineralisation potential, N_0, have been published for related soils (Herlihy and O'Keeffe, 1983).

Table 1: Summary of variables 1978-1985

Variable[1]	Units	N[2]	Mean	SD	Min	Max
OrgC	%	111	2.32	0.66	1.11	4.85
TotN	%	111	0.26	0.06	0.13	0.44
Nmin (0-60cm)	kg ha $^{-1}$	68	234.63	86.59	94.00	445.00
BiomC	kg ha $^{-1}$	78	1744.46	609.89	524.00	3439.00
DeltaN	mg kg $^{-1}$	106	44.35	15.34	12.00	105.50
$CaCl_2N$	mg kg $^{-1}$	106	152.69	71.10	36.75	343.00
$NaHCO_3$ UV	Abs. Units[5]	79	0.50	0.19	0.26	1.30
$Ba(OH)_2$ glucose	mg kg $^{-1}$	106	374.35	185.80	105.00	1100.00
YrsTill	Years	114	6.71	7.18	1.00	50.00
YrsLey	Years	86	8.27	4.68	3.00	30.00
FertN (a)[3]	kg ha $^{-1}$	84	90.40	55.79	37.50	281.25
FertN (b)[3]	kg ha -1	78	132.01	60.70	37.50	283.25
RainA-J	mm (total)	87	196.85	47.86	76.00	277.00
RainA-S	mm (total)	87	426.60	69.70	217.00	603.00
TempA-J[4]	C	87	10.60	0.61	9.50	11.50
SR Jl-S[4]	J m^{-2}	87	1069.27	108.80	831.40	1250.70
RY	%	114	86.69	11.13	50.70	100.00
Nmax	kg ha^{-1}	114	97.48	62.73	0.00	273.00
Nopt	kg ha^{-1}	114	79.67	57.34	0.00	222.00
N (lsd)	kg ha^{-1}	114	51.14	59.37	0.00	240.00

1 Agronomic parameters relate to yield of sugar. Sample depths are 0-20 cm, except Nmin depth = 0-60 cm.

2 Number of observations.

3 Fert N (a) = Fertiliser N only;
Fert N (b) = Sum of N from fertiliser, clover and organic manure.

4 Mean daily values; temperature is air temperature

5 Absorbance at 260nm.

Nmin, biomass C and mineral N flush: In the more fertile of the soils used in this study, Nmin accumulated progressively in the 0-60 cm profile from a minimum of circa 75 kg N ha^{-1} in January to a maximum of 350-400 kg N ha^{-1} at the end of June, which coincided with the subsequent rapid uptake by sugar beet (Herlihy, unpublished). Even when excessive rainfall diminished the quantity of Nmin, it was replenished rapidly by further mineralisation at times when temperature and soil moisture were adequate (Herlihy ***et al***., 1981). The mean end of June value for Nmin (Table 1) represented 1.6% of total N, based

Table 2: Summary of variables 1983

Variable[1]	Units	Mean	SD	Min	Max
OrgC	%	2.26	0.75	1.11	4.85
OrgC (0-40 cm)	%	1.79	0.57	1.06	4.13
TotN	%	0.28	0.06	0.18	0.44
TotN (0-40 cm)	%	0.24	0.04	0.17	0.37
Nmin (0-60 cm)	kg ha $^{-1}$	239.42	77.76	129.00	445.00
BiomC	kg ha $^{-1}$	1577.68	483.90	895.00	2811.00
BiomC (0-40 cm)	kg ha $^{-1}$	2421.03	725.82	1380.00	3783.00
CO_2C	mg/kg $^{-1}$	130.00	50.00	30.00	230.00
CO_2C (0-40 cm)	mg kg $^{-1}$	110.00	30.00	60.00	190.00
Nfum[2]	kg ha $^{-1}$	299.02	74.93	182.91	477.75
Nflush (a)[2]	kg ha $^{-1}$	212.31	68.34	106.47	382.20
Nflush (b)[2]	kg ha $^{-1}$	270.00	80.91	144.69	447.72
DeltaN (a)[3]	mg kg $^{-1}$	43.61	9.41	24.50	63.00
DeltaN (b)[3]	mg kg $^{-1}$	52.12	10.23	34.50	79.50
$CaCl_2N$	mg kg $^{-1}$	212.37	65.80	84.00	343.00
$CaCl_2N$ (0-40 cm)	mg kg $^{-1}$	171.84	41.10	73.50	239.75
$NaHCO_3$ UV	Abs. Units[6]	0.38	0.09	0.26	0.57
$NaHCO_3$ UV (0-40 cm)	Abs. Units[6]	0.38	0.07	0.26	0.52
$Ba(OH)_2$ glucose	mg kg $^{-1}$	454.77	237.97	131.00	1100.00
$Ba(OH)_2$ glucose (0-40 cm)	mg kg $^{-1}$	328.87	144.77	114.50	755.00
KClN	mg kg $^{-1}$	66.04	18.41	35.00	94.50
EUF Nsol (1+2)	mg kg $^{-1}$	44.82	10.95	29.83	71.73
EUF Norg (1+2)	mg kg $^{-1}$	31.71	7.33	22.50	47.30
EUF soilN	mg kg $^{-1}$	197.84	46.07	135.00	303.00
EUF soilN (0-40 cm)	mg kg $^{-1}$	184.99	39.30	135.50	288.00
YrsTill	Years	7.52	7.47	1.00	35.00
YrsLey	Years	8.32	3.04	3.00	15.00
FertN (a)[4]	kg ha $^{-1}$	87.30	54.45	37.50	240.00
FertN (b)[4]	kg ha -1	136.79	63.50	59.50	268.05
RainA-J	mm (total)	223.10	27.72	199.00	277.00
RainA-S	mm (total)	459.68	84.81	375.00	603.00
TempA-J[5]	C	9.88	0.26	9.50	10.20
SR Jl-S[5]	J m^{-2}	1150.60	60.60	1082.19	1235.89
RY	%	87.75	8.74	69.58	100.00
Nmax	kg ha^{-1}	91.48	52.06	0.00	208.00
Nopt	kg ha^{-1}	71.16	43.94	0.00	162.00
N (lsd)	kg ha^{-1}	38.06	65.95	0.00	240.00

1 Agronomic parameters relate to yield of sugar. Sample depths are 0-20 cm, unless stated.
2 N=30, otherwise N=31.
3 Delta N (a) = Standard 14 day incubation;
Delta N (b) = Pre-leached 21 day incubation.
4 Fert N (a) = Fertiliser N only;
Fert N (b) = Sum of N from fertiliser, clover and organic manure.
5 Mean daily values; Temperature is air temperature.
6 Absorbance at 260nm.

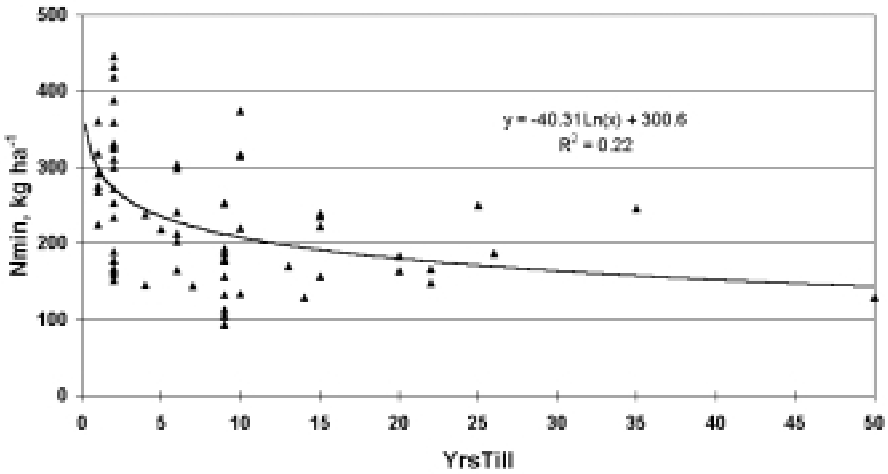

Figure 1: Variation of soil mineral N (Nmin) in the 0-60cm profile in June with number of years tillage (YrsTill).

on an assumed 15000 kg ha^{-1} total N in the 0-60 cm profile, although N mineralised over the full season was likely to be higher than this. Based on the mean values for the 0-20 cm depth in Table 2, it is evident that BiomC constituted 2.6% of the organic C, which exceeded the value of 2.0% considered to represent soils that are in equilibrium between input and offtake of C. Nflush constituted 2.8-3.5% of the total N, depending on method of measurement. Both were in the range observed in other work (Carter and Rennie, 1982). The active pool of labile or comparatively more available N has been shown to be of the order of 15% of the total N in the 0-20 cm depth of similar soils, based on typical values for biomass N and potentially mineralisable N (Herlihy and O'Keeffe, 1983). This greatly exceeds the annual release of Nmin. It is similar, however, to other estimates of the active N pool, and indicative of the reserve of organic N that may readily become available over time.

Long-term trends in Nmin and biomass C: Figure 1 illustrates the trend in Nmin in the 0-60 cm profile at the end of June ***versus*** the duration of years tillage. The best fit of the data was provided by the logarithmic curve. The wide scatter in data-points is evidence of the possible effects of other contributing factors, which may include some difference in sampling times within or between years, and also effects of other environmental, soil and rotation variables. However, regression of Nmin against various combinations of YrsTill, ratio of

YrsTill:YrsLey, both logged and un-logged, and Rain (A-J) did not result in a higher R^2 value. It has previously been observed that variation within index or soil groups can be comparable to variation between groups (Harrison, 1995). There was a similar trend in BiomC 0-20 cm with years tillage (Figure 2), and a similar scatter in data points. The relationship between Nmin and BiomC was non-significant, possibly because of difference in sample depth.

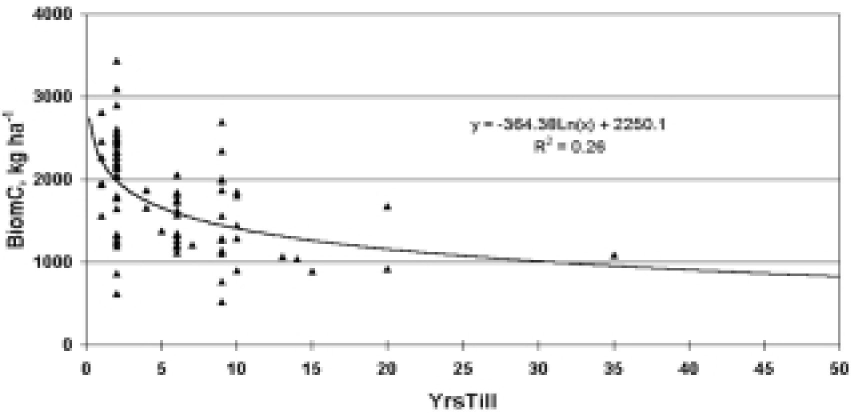

Figure 2: Variation of biomass C (BiomC) in the 0-20 cm depth with number of years in tillage (YrsTill) for a range of years.

BiomC was more highly correlated with YrsTill when comparison was confined to one year (Figure 3). It was also evident that variation was more likely in the surface layer, possibly due to higher levels of labile organic matter and a greater flux of biological activity.

The mean trend value of Nmin was 300 kg ha^{-1} after one year tillage, based on Figure 1. After 3, 5, 10, 20 and 50 years, Nmin was 85%, 78%, 69%, 60%, and 47%, respectively, of the one year value. BiomC declined somewhat more rapidly over time - to 37% of the initial value after 50 years (Figure 2). It is evident that the relative magnitude of Nmin over the intermediate and longer term reflects a continuing contribution of labile N and of the likely effect of organic N previously accumulated under ley.

Generally, the relatively more rapid rate of decline in both Nmin and BiomC in the early years of tillage was evident in these results. It was also evident, however, that there was a continued decline in both over the longer term, which has implications for the operative time-span of release of N from organic reserves and the sustainability of the soil N supply.

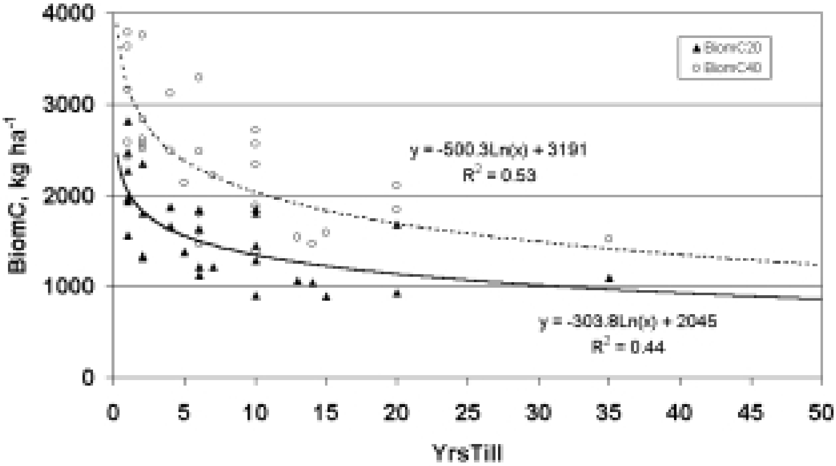

Figure 3: Variation of biomass C (BiomC) in the 0-20 cm and 21-40 cm depths with number of years in tillage (YrsTill) for one year (1983).

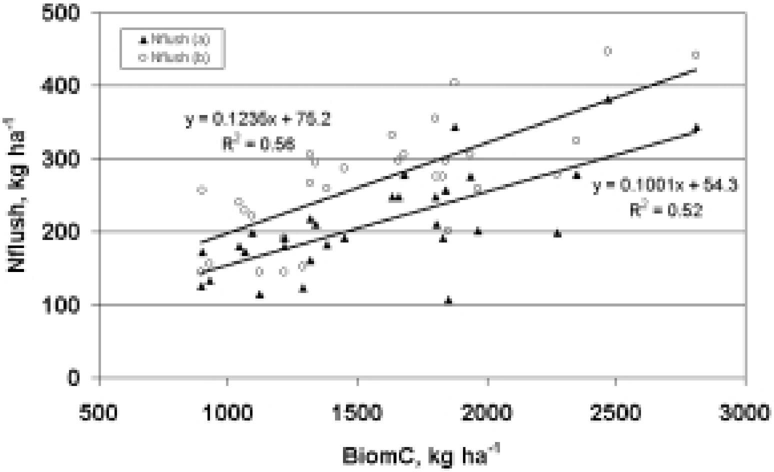

Figure 4: Variation of mineral N flush (Nflush) with biomass C (BiomC); (a) and (b) refer to basal N mineralisation corrections of 0-10 or 10-20 days incubation.

Relationship of mineral N flush with biomass C: The microbial biomass functions both as a sink or source of nutrients and as a mediator of biological activity. It may also to some extent act as a proxy for soil N availability (Nunan ***et al.***, 1998, 2000). However, the flush of mineral N (Nflush) induced by fumigation was also used in this study in the expectation that, as an estimate of microbial N, it would provide an indication of the likely extent of labile organic N. Its relationship with BiomC (Figure 4) varied with the procedure employed for correction of basal mineralisation of non-cellular N sources. Nevertheless, given the source of the Nflush, the degree of the relationship (R^2 = 52-56%) quite likely reflected the fact that biomass partitions into active and inactive components (Bremer and van Kessel, 1990; Puri and Ashman, 1998). One very anomalous site was disregarded for these comparisons. Nflush (a) and Nflush (b) constituted ***circa*** 12-15% and 15-20%, respectively, of BiomC for BiomC values of 1000-3000 kg ha^{-1}, based on the data in Figure 4.

Agronomic variables *versus* independent variables

The general relationships between the various agronomic and other variables are summarised in the correlation matrices (r-values) in Tables 3 and 4. The agronomic variables included the N inputs defined as the maximum (Nmax) or optimum (Nopt) for sugar yield, based on fitted dose-response curves (Herlihy, 1992a), or based on analysis of variance and tests for least significant difference (lsd), and relative yield (RY), which is the yield at 0N expressed as a percentage of the yield at Nopt. The results in Table 3 for the period 1978-85 indicate the decreasing order in terms of r-value for the significant variables ***versus*** Nopt, the most relevant estimate of fertiliser N requirement, as follows:

Log YrsTill > BiomC = Nmin > TotN >OrgC > $CaCl_2$N.

Here Nmin refers to the 0-60 cm depth, because this provided a higher degree of correlation than other sample depths. The evaluation, which excluded any consideration of the role of secondary or ancillary variables, indicated that only the r-value for log YrsTill was sufficiently high to provide some basis for prediction of N inputs. Generally, relationships between the dependent agronomic variables and predictors of N availability conform to a logarithmic distribution. However, in Table 3 the log term was used only for years tillage, because of the lesser and inconsistent improvement in r-value for the logs of soil tests. In contrast, for the 1983 databank (Table 4), the log terms were generally superior for soil tests also. However, logs of tests were included only for the correlation with agronomic variables to enable meaningful comparison of non-log values between tests. For these wider range of tests in one year (Table 4), the decreasing order of significant r-value for the log of each variable ***versus*** Nopt was:

$CaCl_2N$ > $NaHCO_3$ UV > YrsTill = DeltaN (b) > Nflush (b) = KClN > CO_2C.

DeltaN (b) refers to the 21-day incubation, which was superior to the lesser incubation times for this cumulative mineralisation procedure on pre-leached samples. The lack of contribution from Nmin was notable, and may have reflected high rainfall. However, none of the tests correlated sufficiently strongly with Nopt to provide a basis for prediction of N inputs.

Role and relevance of significant variables: Of the significant variables in Table 3, microbial biomass (BiomC) is a source and sink for labile N and the active agent in mineraliasation and immobilisation. Because of this integrative role, it has been found to relate better to production of mineral N than indices of any single step (Burton & McGill, 1992) and to be sensitive to changes in soil management (Powlson & Jenkinson, 1981), which is attributable more to the activity of the biomass as distinct from its N content (Bonde ***et al.,*** 1988; Burton & McGill, 1992). $CaCl_2N$ determined by refluxing and digestion provides an estimate of labile amino acid and peptide sources of N. In contrast, Nmin provides a direct estimate of the available N in a specified depth of profile. Where mineralisation of organic N is its principal source, the measurement needs to coincide closely with time of maximum accumulation, if it is to provide a useful estimate of fertiliser N requirements. Often, however, Nmin is used where the objective is to quantify the residual N from the previous season (Danke and Johnson, 1990; Mengel, 1985). A direct profile measurement of Nmin, depending on the specific circumstances and its timing, can provide a guideline for the supply of soil N, although sampling to 60 cm, for instance, in our soils would be a difficult task on a routine scale.

Whereas, significant biological and chemical tests have some justifiable basis in assessment of N availability, the range of r-values obtained here was such as not to justify their application for prediction of N inputs and, by extension, of N availability. In terms of fertiliser inputs, Nopt can be considered the more relevant of the dependent variables, and the one for which calibration with an estimate of soil N availability is required. Unusually, for the KCl extract, the significance was highest for N (lsd). This inconsistency between significant terms for one year, compared with a range of years (Tables 3 and 4) is not unexpected. Relationships that are limited in terms of years or of range of soils, for example, can to be unrepresentative of more extended observations (Greenwood, 1986; Thicke, ***et al.,*** 1993).

The independent variables, generally, were poorly correlated with each other over all years (Table 3), with not more than 28% of the variation accounted for between any pair of soil tests of N availability, ***i.e.*** other than OrgC and TotN. Relationships were stronger for comparisons restricted to one year (Table 4),

Table 3: Correlation matrix 1978-1985

Variable	N*	YrsTill	LnYrsTill	YrsLey	OrgC	TotN	Nmin	BiomC	DeltaN	$CaCl_2N$	$NaHCO_3$	$Ba(OH)_2$	RY	Nmax	Nopt	N(lsd)
YrsTill	114	1.00														
LnYrsTill	114	0.85	1.00													
YrsLey	86	0.23	0.03	1.00												
OrgC	111	-0.36	-0.42	0.01	1.00											
TotN	111	-0.36	-0.40	0.02	0.76	1.00										
Nmin	68	-0.36	-0.47	-0.04	0.23	0.42	1.00									
BiomC	78	-0.44	-0.51	-0.05	0.41	0.25	0.15	1.00								
DeltaN	106	-0.11	-0.24	0.07	0.14	0.21	-0.05	0.27	1.00							
$CaCl_2N$	106	-0.23	-0.30	0.11	0.47	0.48	0.10	0.19	0.18	1.00						
$NaHCO_3$	79	-0.36	-0.34	0.04	0.26	0.18	-0.03	0.38	0.51	0.04	1.00					
$Ba(OH)_2$	106	-0.24	-0.31	0.18	0.34	0.37	-0.06	0.05	0.34	0.53	0.26	1.00				
RY	114	-0.41	-0.45	-0.06	0.17	0.18	0.32	0.33	0.20	0.15	0.11	0.06	1.00			
Nmax	114	0.49	0.55	-0.02	-0.30	-0.32	-0.42	-0.39	-0.16	-0.17	-0.09	-0.08	-0.72	1.00		
Nopt	114	0.45	0.54	-0.04	-0.28	-0.33	-0.38	-0.38	-0.18	-0.19	-0.07	-0.09	-0.79	0.95	1.00	
N (lsd)	114	0.32	0.44	-0.17	-0.19	-0.27	-0.30	-0.25	-0.10	-0.19	-0.01	-0.15	-0.59	0.63	0.72	1.00

* Number of observations

Table 4: Correlation matrix of soil tests, and of log of soil tests with agronomic variables, for 1983[1]

Variable[2]	LnYrsTill	OrgC	TotN	Nmin	BiomC	CO_2C	Nflush (a)	Nflush (b)	DeltaN (b)	$CaCl_2N$	$NaHCO_3$	$Ba(OH)_2$	KClN	EUF-Nsol	EUF-Norg	EUF-SoilN
LnYrsTill	1.00															
OrgC	-0.54	1.00														
TotN	-0.58	0.88	1.00													
Nmin	-0.35	0.12	0.20	1.00												
BiomC	-0.66	0.37	0.58	0.38	1.00											
CO_2C	-0.58	0.61	0.63	0.11	0.38	1.00										
Nflush(a)	-0.56	0.51	0.69	0.26	0.63	0.48	1.00									
Nflush(b)	-0.60	0.53	0.72	0.28	0.54	0.52	0.91	1.00								
DeltaN(b)	-0.55	0.23	0.41	0.15	0.46	0.22	0.52	0.68	1.00							
$CaCl_2N$	-0.81	0.60	0.61	0.35	0.51	0.48	0.44	0.47	0.52	1.00						
$NaHCO_3$	-0.74	0.62	0.49	0.20	0.28	0.58	0.29	0.42	0.43	0.82	1.00					
$Ba(OH)_2$	-0.52	0.47	0.41	0.07	0.11	0.37	0.36	0.41	0.41	0.51	0.53	1.00				
KClN	-0.64	0.51	0.56	0.17	0.32	0.48	0.49	0.47	0.30	0.69	0.60	0.41	1.00			
EUF Nsol	-0.61	0.56	0.67	0.24	0.43	0.45	0.61	0.68	0.44	0.62	0.55	0.40	0.71	1.00		
EUF Norg	-0.43	0.47	0.57	0.09	0.37	0.22	0.45	0.45	0.26	0.50	0.35	0.33	0.63	0.87	1.00	
EUF SoilN	-0.57	0.55	0.66	0.20	0.42	0.39	0.58	0.63	0.39	0.60	0.51	0.40	0.71	0.99	0.94	1.00
RY	-0.24	0.08	0.11	0.17	0.14	0.30	0.27	0.33	0.20	0.24	0.19	-0.08	0.28	0.29	0.04	0.22
Nmax	0.34	-0.30	-0.28	-0.20	-0.37	-0.25	-0.27	-0.31	-0.31	-0.33	-0.31	-0.08	-0.34	-0.26	-0.13	-0.22
Nopt	0.40	-0.27	-0.28	-0.15	-0.33	-0.36	-0.27	-0.38	-0.40	-0.42	-0.41	-0.08	-0.38	-0.31	-0.08	-0.24
N (lsd)	0.35	-0.18	-0.18	-0.11	-0.27	-0.32	-0.29	-0.29	-0.29	-0.43	-0.41	-0.21	-0.51	-0.18	-0.15	-0.18

1 Logs of soil tests were used only for correlation with agronomic variables.
2 N=31

notably for $CaCl_2$ ***vs.*** $NaHCO_3$, $CaCl_2$ ***vs.*** log YrsTill, $NaHCO_3$ ***vs.*** log YrsTill, and Delta N (b) ***vs.*** Nflush (b). The percent variation accounted for was in the range 46-67%.

Agronomic variables, soil tests and ancillary variables

For the more complete group of 86 sites for the years 1980-85 in terms of all soil management criteria, stepwise multiple regression analysis was performed between the dependent agronomic variables and selected soil tests, or soil management criteria, together with the ancillary weather and soil series data. Regressions were performed for the following groups: (a) medium texture soils, ***i.e.*** Clonroche and Elton series, (b) other soils, ***i.e.*** Athy series, Kellistown series and the predominantly light-texture soil association 15, and (c) all soils.

Relevance of Nmin and rainfall: Table 5 summarises the output for the various groups for the most relevant soil-tests from the initial correlation matrix (Table 3). Of the soil tests, only Nmin proved to be consistently significantly related to Nopt for the various soil groups. Rainfall was the most consistent ancillary variable to contribute to the regressions, especially July-September rainfall (Rain Jl-S), although the signs for the coefficients were not always consistent with the expected trend for variables other than Rain Jl-S with Nmin. Combinations of soil tests and management data did not improve R^2 values.

Table 6 gives parameter estimates for regression equations for significant variables common to all soil groups, ***i.e.*** for Nmin with Rain Jl-S. The overall R^2 value was 22.5%, compared with a value of 14.4% for Nmin only based on Table 3. The results indicate the reduced availability of the end of June levels of Nmin with increasing levels of rainfall in the period of maximum crop uptake. Also, it is evident from the regression coefficients that medium texture soils required substantially less adjustment for rainfall than the other, generally lighter, soils where Nmin provided the estimate of N availability.

Limitations of soil tests for N: Although soil tests of N availability have been shown to correlate with crop response or N uptake, the most satisfactory relationships have been found under narrowly controlled experimental conditions, or for relatively uniform soils, or for climatic conditions where mineralisation is stabilised. They have not been widely implemented in soil-testing programs, particularly under more variable conditions, because of the resultant unpredictability both in the mineralisation of organic N and in the profile distribution of mineral N. The relevance of chemical and biological tests has been questioned, in particular, for regions with heterogeneous soils and humid climate for which a rotation N index on the basis of residual mineral N from the preceding

Table 5: Significant terms and R^2 values for Nopt *versus* soil tests with auxiliary variables

Soil test	Soil category					
	Clonroche & Elton soil series	R^2	Other soil series	R^2	All soils	R^2
Nmin(0-60cm)	Nmin, RainJl-S, TempA-J	29.4*	Nmin, RainJl-S	33.1**	Nmin, RainA-J, RainJl-S, TempA-J	28.6***
LnNmin (0-60cm)	LnNmin, RainJl-S	23.7*	LnNmin, RainJl-S	29.1*	LnNmin, RainA-J, RainJl-S, TempA-J	26.3**
BiomC (0-20cm)	-	NS	BiomC	25.4***	BiomC	14.2***
LnBiomC C(0-20cm)	-	NS	LnBiomC	23.5***	LnBiomC	11.8**
$CaCl_2$ (0-20cm)	-	NS	$CaCl_2$, RainJl-S	16.5*	$CaCl_2$, SR Jl-S	10.4*
Ln$CaCl_2$ (0-20cm)	-	NS	Ln$CaCl_2$, RainJl-S	18.9**	Ln$CaCl_2$, RainA-J	13.0*
$CaCl_2$ (0-40cm)	-	NS	$CaCl_2$, RainJl-S	14.2*	$CaCl_2$,SR Jl-S	12.0*
Ln$CaCl_2$ (0-40cm)	-	NS	Ln$CaCl_2$,RainJl-S	16.2*	Ln$CaCl_2$, RainA-J	13.5*

*, **, *** Significant at $P < 0.05$, 0.01 and 0.001 for the soil test term

Table 6: Parameter estimates for variables common to all soil groups for the relationship Nopt *versus* Nmin

Variable	Coefficients	S.E.	P-value	Regression statistics	
		Clonroche & Elton soil series			
Intercept	45.200	40.390	0.272	R^2	24.1
Nmin (0-60 cm)	-0.212	0.104	0.049	S.E.	52.24
RainJl-S	0.338	0.138	0.021	No.	34
		Other soil series			
Intercept	40.519	67.375	0.552	R^2	33.1
Nmin (0-60 cm)	-0.342	0.113	0.005	S.E.	54.47
RainJl-S	0.650	0.296	0.036	No.	34
		All soils			
Intercept	73.518	33.436	0.031	R^2	22.5
Nmin (0-60 cm)	-0.255	0.077	0.002	S.E.	54.49
RainJl-S	0.308	0.120	0.013	No.	68

crop, for example, has been deemed to be more practicable (Jenkinson, 1984). Management-based or rotation criteria have also been shown to be appropriate as an estimate of availability under conditions of high and variable N mineralisation in spring, such as arises in cropping systems that involve ley-arable farming.

Agronomic variables, soil management and ancillary variables

In the evaluation of the soil management variables by stepwise multiple regression (SAS, 1989), the contribution from years in ley (YrsLey) was not significant, although both long and short term effects of leys on N mineralisation can be expected for soils in grass-arable rotations. Greenwood (1986), for example, considered that the interval to establish a new equilibrium for soil N status would be at least 50 years following any change in practice between ley and arable farming in the UK. Since it is likely that the effect of duration in ley was distorted or masked by inclusion of the equally relevant duration in tillage, the ratio YrsTill /YrsLey was included as an interaction term. The product of the variables was considered inappropriate, because very contrasting combinations would provide similar product values even within the likely range of data.

The results of the stepwise regressions indicated that YrsTill and the ratio term provided the best estimate of Nopt. Of the ancillary variables, rainfall was the only consistent significant term. The signs of the coefficients for fertiliser use in the preceding ley were inconsistent. Others have noted that build up of organic N depends on the annual input of organic matter, and is little affected by fertiliser N within the normal range (Greenwood, 1986, Webb and Sylvester-Bradley, 1994), contrary to its use in some index systems. Also, the results did not provide a basis for distinguishing between different soils groups, or between cut or grazed leys in terms of their effects on Nopt. This possibly reflects the fact that many cut swards are also occasionally grazed, or the fact that only the most relevant or dominant variables prove significant when a wide array of combinations of very diverse variables are tested. Furthermore, fertiliser N requirement was unrelated to either maximum crop yield or date of sowing (Herlihy, unpublished), although it did relate significantly to the latter in single site experiments (Blagden, 1982).

Selection of regression models: Subsequently, the R^2 selection procedure (SAS, 1989) was applied to regression of Nopt on all linear and log combinations of YrsTill and the ratio term, with growing season rainfalls for the intervals April-June (Rain A-J) and July-September (Rain Jl-S). The objective was to select an array of regression models. The R^2 values obtained for the most significant combinations of 2, 3 or 4 independent variables (Table 7) were in a

Table 7: Regression models and parameter estimates for Nopt *versus* years tillage, ratio years tillage: years ley and rainfalls

Model 1		Model 2		Model 3		Model 4		Model 5	
Variable	**Estimate**	**Variable**	**Estimate**	**Variable**	**Estimate**	**Variable**	**Estimate**	**Variable**	**Estimate**
Intercept	2.00	Intercept	-29.72	Intercept	-18.07	Intercept	38.66	Intercept	71.36
YrsTill	1.70	LnYrsTill	25.86	LnYrsTill	21.12	YrsTill	1.71	YrsTill	1.84
LnRatio	19.84	Ratio	7.30	LnRatio	11.81	LnRatio	18.75	LnRatio	18.09
RainA-J	0.165	RainA-J	0.111	RainA-J	0.139	RainA-S	0.148	-	-
RainJl-S	0.169	RainJl-S	0.161	RainJl-S	0.176	-	-	-	-
R^2	0.33	R^2	0.33	R^2	0.32	R^2	0.31	R^2	0.29
P(<)	0.0001	P(<)	0.0001	P(<)	0.0001	P(<)	0.0001	P(<)	0.0001

narrow range of 29%-33%, similar to that often observed also in evaluation of soil P and K tests. Given the overall level of variability associated with results from experiments conducted over a range of years and locations, and the complexity of N transformations, the moderate level of correlation was not unexpected. It has been noted that the goodness of fit of any measure of N response and any given factor was improved with comparisons limited to one year or to otherwise idealised conditions (Greenwood, 1986; Thicke ***et al***, 1993).

Sensitivity tests: Sensitivity testing of model 1 for a range of representative values for each variable (Table 8) indicated the wide variation in Nopt obtainable at constant years tillage. The range at 5 years tillage, for example, was 38-109 kg N ha^{-1} for varied combinations of the ratio term, mean rainfall, or rainfalls that deviated plus or minus 100 mm for the combined intervals. Such a wide range is consistent with that observed by others (Harrison, 1995), and not unexpected from large-scale field experiments. Contrastingly, the 76 kg N requirement derived from the 5 years tillage and 3 years ley combination was similar to the value for the 10 years tillage and 20 years ley combination. Contrary to current practice, this implies a lasting effect of prolonged duration in ley, which is consistent with other observations (Greenwood, 1986) and with the distribution of Nmin over the intermediate and longer term (Figure 1). It also illustrates the limitation of ignoring the effect of ley after some arbitrary number of years in tillage.

Table 8: Optimum N inputs based on sensitivity tests of regression model 1

YrsTill	YrsLey	Ln(YrsTill/YrsLey)	RainA-J	RainJl-S	Model Nopt
1	3	-1.10	200	230	54
1	20	-3.00	200	230	16
5	3	0.51	150	180	76
5	3	0.51	200	230	93
5	3	0.51	250	280	109
5	20	-1.39	150	180	38
5	20	-1.39	200	230	55
5	20	-1.39	250	280	72
10	3	1.20	200	230	115
10	20	-0.69	200	230	77
15	3	1.61	200	230	131
15	20	-0.29	200	230	94
20	3	1.90	200	230	146
20	20	0.00	200	230	108
35	3	2.46	200	230	182
35	20	0.56	200	230	145
50	3	2.81	200	230	215
100	3	3.51	200	230	314

When total seasonal rainfall is partitioned as shown, the effect equates to plus or minus 17 kg N ha^{-1} for each 100 mm rainfall above or below the norm in seasonal terms, as appropriate. It is evident that the effect is only substantial between very contrasting years or areas. When sensitivity tests were performed on models 2 and 3, either unaccountably high or unacceptably low outputs were obtained for optimum N at high combinations of the independent variables, which indicated their practical limitations, despite R^2 values comparable to model 1.

Practical significance of regression model: Figure 5 illustrates the relationship between the experimental and model Nopt values. The very large deviation from the mean trend line is evident for some sites. However, the trend line provides a basis for calibrating fertiliser N inputs over an extended range of soil fertility categories. The scatter in the data points is not untypical and, if necessary, can be accommodated by an appropriate confidence interval or equivalent. Some recognition of the wide scatter may be presumed to justify inputs that are set higher by 10-20%, or by a fixed amount of 20-30 kg N given the distribution of scatter, or by use of some calculated confidence limit. However, other results indicate that, due to the latitude and imprecision of optima based on response curves, the use of the mean values already provide an accommodation of 20% or more in Nopt before severe restriction is encountered (Herlihy and Hegarty, 1994). Nonetheless, some latitude may be justified, given that fertiliser and other nutrient distribution in experimental plots is less variable than in large commercial field-areas.

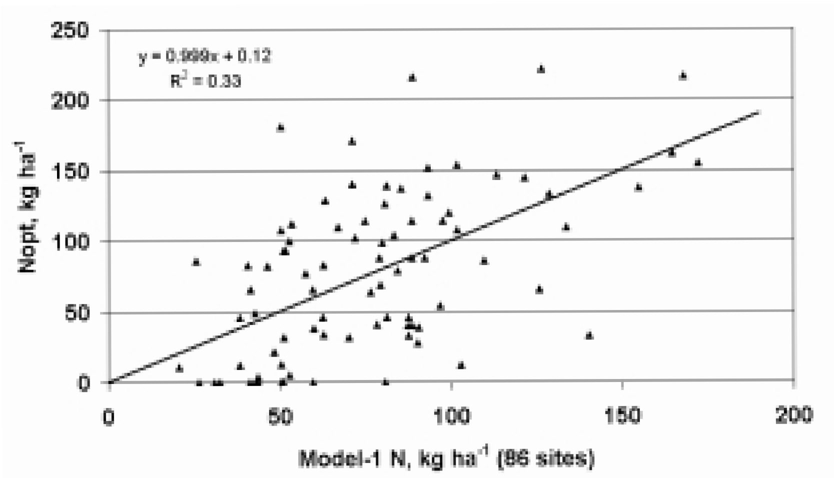

Figure 5: Experimental optimum N (Nopt) ***versus*** model-1 N values.

The range in the mean Nopt values was ***circa*** 20-170 kg ha^{-1} (Figure 5). This compares with current advice, derived from the same basic criteria, of 45, 80, 120 and 150 kg ha^{-1} for four index categories designated by an index system specific to the sugar beet data (Herlihy, 1992a). More generally, such fixed values for an index system may reflect limited calibration data, so that distinctions are provided only for a limited number of category groups. Also, indices do not provide for circumstances where higher or lower than average inputs are justified, as for example in accommodating extremes within index categories or where a long duration in continuous tillage extends requirements.

Overall, model values were within +/- 30 kg N ha^{-1} of the observed optimum in 42% of cases and within +/- 90 kg N ha^{-1} in 7%, very similar to the corresponding 43% and 8% observed for the latest revision of the UK arable recommendations (Dampney, 2000). This coincidence of distributions suggests that there may be a limit to the degree of correlation attainable in large-scale field trials in broadly similar environments. Also, it implies that the mean regression values have an equivalence in relative terms with the inputs designated by the different UK approach.

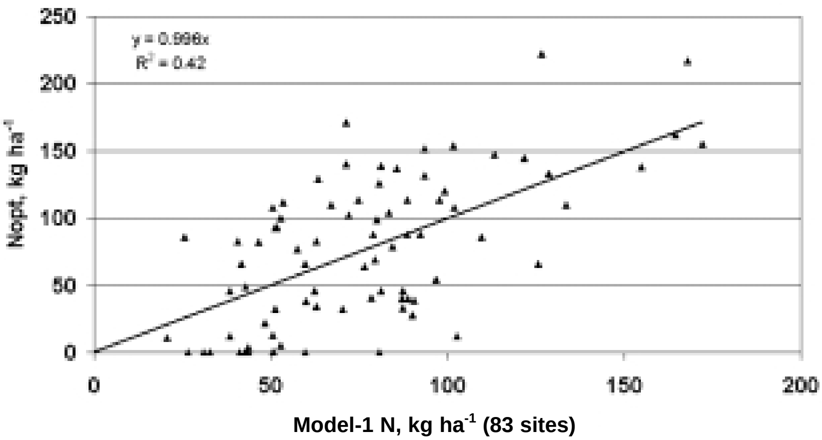

Figure 6: Experimental optimum N(Nopt) ***versus*** model-1 N values with three outliers excluded.

When the most extreme three outliers were excluded (Figure 6), the R^2 increased from 33% to 42%, which is relatively high for nutrient calibration studies. Although arbitrary, this may point up the inevitability of the variation encountered under field conditions. It certainly suggests that the relationship with predicted values was noticeably limited by a very small minority of sites, possibly because of crop management limitations on such sites. Otherwise, the R^2 of 42% suggests that the relevant variables are well represented in the model in the vast majority of cases, and that the prediction model basically conforms to an acceptable standard.

Sustainability of contribution of soil N reserves: This study illustrates, directly and implictly, the extent and importance of sustainable long-term release of N from soil reserves that are initially substantial, both in the projection by model 1 for a gradual increase in Nopt (Figure 7), and in the quantity and protracted decline of Nmin over time (Figure 1). The long-term trend and projection for model 1 for previous ley duration of 20 years (Figure 7) was broadly consistent with the Nmin values, on the assumption of an uptake efficiency of 70% for available soil N and fertiliser N, and a required N uptake of 240-280 kg N ha^{-1} for optimum yield of sugar in our environment. The values shown for the model-N output were approximately 38 kg N ha^{-1} lower than those for a ley duration of 3 years, for example, which would reflect virtually continuous tillage with a minimal ley break. It has been noted that the biomass N and active N pools in these soils are of the order of 15% of the total N (Herlihy and O'Keeffe, 1983), although this proportion may decline over time. The likely 35% that is stabilised N with a half-life of 27 years (Paul and Juma, 1981), however, can also provide a large continuing source of slowly available N, even with a low rate of decomposition (Greenwood, 1986).

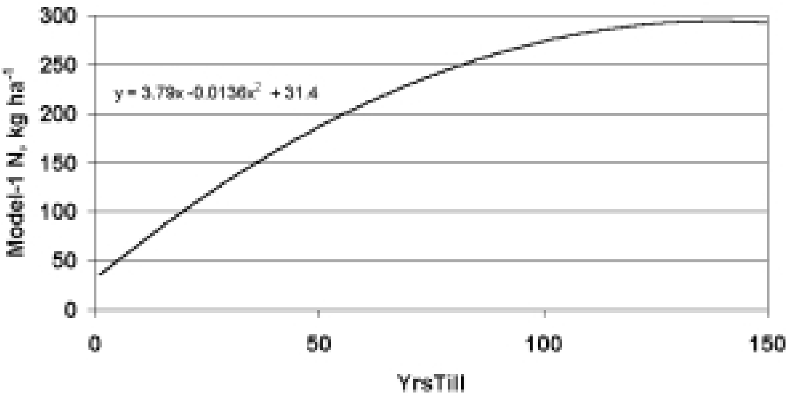

Figure 7: Model N prediction ***versus*** years tillage (YrsTill) for conditions of 20 years ley and mean rainfall.

Residual effects - implications and relevance of rainfall

Preceding winter rainfall, which is taken into account in the UK, for example, was not considered relevant in this study. In the UK and Holland, winter rainfall has been used to modify N inputs on the basis of varying effects in spring of residual N from the previous cropping season. Limits have been set on the basis that 200-250 mm November-February rainfall (van der Paauw, 1963; Eagle, 1967), or 700 mm annual rainfall (Dampney, 2000), define an upper limit beyond which the contribution of residual N is likely to be negligible. In Ireland, where field capacity is more quickly replenished, October-February rainfall is probably more relevant, with high levels (Table 9) indicative of less likelihood of any required distinction for residual effects. The different context in Ireland is also evident on the basis of annual rainfall - all meteorological stations representative of arable areas recorded annual rainfalls well in excess of 700 mm for the period 1979-1999.

Table 9: Mean October-February and annual rainfalls (mm) for the years 1979-1999

Location	October-February	Annual
Birr	393	840
Casement	332	730
Cork Airport	649	1241
Johnstown Castle	513	1022
Kilkenny	408	876
Mullingar	468	986
Shannon	498	986

Even in the UK, residual effects and, consequently, winter rainfall have been considered of most relevance on deep clay or silt soils, as opposed to lighter soils where over-winter leaching is prevalent (MAFF, 2000). For loamy sands and sandy loams, 75% of the total residual N was leached at circa 110 mm and 180 mm of excess winter rainfall (Anthony ***et. al.***, 1996; Dampney, 2000).

Growing-season rainfall: In the current study, as noted above, the operative cumulative rainfalls were those for the periods April-June and July-September. There was a wide range in their respective values of 76-277 mm and 141-326 mm in the data bank. Otherwise, April-June rainfall had a pronounced effect on vertical distribution in the 0-60 cm profile, but had little effect on cumulative Nmin unless excessive amounts were recorded in June. Mean depth distributions in ***0***N field-plots in two normal years were 45%, 31% and 24% of the total Nmin in the 0-20, 21-40 and 41-60 cm depths, respectively, and 55%, 24% and 21% in plots treated with fertiliser N at 160 kg ha^{-1}. Comparable values for ***0***N in two wet years were 29%, 33% and 38% (Herlihy, 1983).

Contribution of residual effects: The data presented in this report do not address the issue of residual effects, if any, from previous arable crops, since sugar beet generally was preceded by cereal crops. Given the high rainfall levels (Table 9), the relatively more dominant contribution of N mineralisation in spring, and the generally permeable nature of our arable soils, which cannot be described as nitrate retentive as the relevant UK soils have been (MAFF, 2000), it appears that it may be easy to overstate the case for carry over of significant levels of residual ammonium and nitrate from the previous crop.

The contribution from mineralisable crop components is more complicated. One experiment has shown that mineralisable N can be higher after successive cereals than after root crops, and that the presence of residue of high C/N ratio results in progressive decrease in mineralisation and an eventual immobilisation following high rates of nitrogen (Herlihy, 1972). It has also been noted for sugar beet residues that if the C/N ratio of the residues is wide – where both leaves and crowns are returned - a prolonged period between incorporation and sowing of the next crop is required to complete decomposition, whereas if the C/N ratio is narrow rapid decomposition results in substantial leaching losses before the following crop can use the nitrogen (Whitmore and Groot, 1997).

Notwithstanding the above, residual fertiliser effects on malting barley from N applied to sugar beet or fodder beet have been noted in Ireland, although under rather specific conditions. In one experiment, the effect of fodder beet compared with barley as the preceding crop equated only to 0.05 t ha^{-1} of grain at 81% dry matter, on average (Gately, 1968). In other experiments where the residual yield response was somewhat more pronounced, some critical limitations were noted. In these, winter rainfalls for the years preceding the test crop were only 63% of the long-term average, and residual effects were tested in the absence of further N application (Gately, 1967), which has been shown to enhance the effect. Even so, it was apparent that the residual response was not large, equivalent to 0.19 t ha^{-1} of grain at 81% dry matter, if based on the N input for maximum response of sugar beet, rather than an N input circa 45 kg ha^{-1} higher. In regard to residual effects, it is also relevant to note that as little as 1-3% of N applied to cereals has been found in mineral forms after harvest (MacDonald et al., 1989) and that the N in cereal residues was relatively unavailable to subsequent crops (Hart ***et al.***, 1993).

Impact on N index: The above observations justify consideration, given that the current N index system distinguishes between the residual effects of various arable crops. In addition, it should be noted that some categories of the index are considered misplaced (Thomas ***et al.***, 1998), because of overstating the impact of residual effects, and that it may appear to be aligned with earlier UK versions. As demonstrated in the current report, more weight should be given to years previously in ley in conjunction with years in tillage, and more recognition given to the sustainable release of Nmin over time. The fact that cereals constitute almost 80% of the area of arable crops in Ireland (Fingleton and Cushion, 1999) diminishes the latitude for distinguishing on the basis of previous crop grown in most circumstances, and may further imply a need for revision of the system of N advice for arable crops.

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