AVAILABILITY OF NITROGEN IN ARABLE SOILS – A PERSPECTIVE

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Introduction

The requirement for maximum efficiency in fertilizer use is being emphasised increasingly, in terms both of achieving environmental quality and sustainability and of meeting the demand for cross compliance. In considering the implications for nitrogen (N) use, we need to evaluate what is known qualitatively and quantitatively of the N status of our arable soils, what application this knowledge has in practical terms, and what solutions are available for improving or refining our prediction of fertilizer N inputs. The perspective that is proffered is a personal one and draws selectively on the outcome of research at Johnstown Castle. The objective is to provide a review, if only partial, of the availability and distribution over time of N in our arable soils, and the issues and inferences that arise in terms of fertilizer N inputs. It is implicit that on-going developments should reflect changes in fertility status of soils and in the way such changes are monitored.

Soil N distribution and availability

The total quantity of N in the root profile (60 cm depth) of our arable soils is typically of the order of 15000 kg ha^{-1}, about 98% of which is in the organic form. This contrasts with the relatively small quantity of soil N exploited by an annual crop. Even in the 20 cm plough layer, total N (kg ha^{-1}) varies from about 5000 in loamy sands to 6500 in sandy loams and 8500 in loams. Given such quantities, it is of interest to consider the composition and relevance of the organic N, its potential for supplying available ammonium and nitrate, *i.e.* mineral N (Nmin), by the process of mineralisation, and the characteristics and distribution of the mineralisation process *per se*. However, the published information is not necessarily comprehensive. Whereas there has been considerable investigation over the years of the agronomy and the associated N requirements of field crops in this country (Conry, 1984, 1997; Gately, 1967, 1968a, 1968b; Herlihy,1992a; Herlihy and Carroll,1969; Herlihy and Hegarty, 1994), there has been more limited input into the descriptive processes associated with soil N and its availability in arable soils.

Various methodologies have been employed in attempts to define and quantify the pool of available N in the soil reserves. One approach has involved chemical fractionation following acid hydrolysis (Figure 1), which cannot be assumed to be a sensitive method. Nonetheless, chemical fractionation of soils has shown that significant changes occur in specific groups, such as amino acid and hexosamine fractions, despite the difficulty of observing measurable changes under field cropping within limited time spans. It is known that the compounds from which the amino acid and hexosamine sources derive, and which constitute approximately 50% of the total N, exist in complexes with clays and humic substances (Schulten and Schnitzer, 1998), which limits their availability. There are also large quantities that are unidentifiable or insoluble and some 15%, expressed as ammonium, that likely arises as a product of the acid hydrolysis. Such fractionation has been of limited application in defining and quantifying the labile organic N, *i.e.* the biologically decomposable quantity, which is much less than 50% of the total. Although the remaining sources continue to be poorly understood, it is considered that some recalcitrant compounds may even have a role in long-term supply of N (Schulten and Schnitzer, 1998), and indeed in very long term experiments as much as 50% of the total soil organic matter has been decomposed. In the context of more immediate N supply, a significant decrease - of *circa* 14% - was observed in the amino acid and hexosamine sources after only four years of tillage (Herlihy and O'Keeffe, 1983), indicative of the relevance of some specific partitioning of organic N.

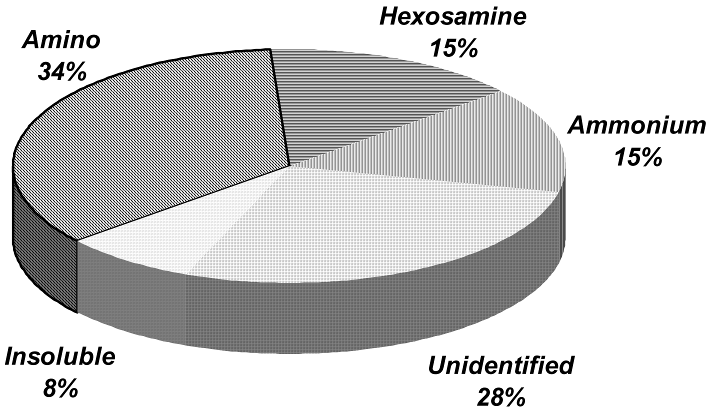

Figure 1: Mean organic-N fractions in 6N HCl hydrolysates of soils (Herlihy, unpublished).

In recognition of the limitations in allocating availability to specific organic fractions, isotopic (^{15}N) and modelling procedures have been combined to quantify the total pool of potentially available organic nitrogen. Jansson (1958) first used ^{15}N to show that the cycle of mineralisation and immobilisation involves an active phase that constitutes 10-15% of the total organic N, which is in slow equilibrium with a larger passive phase. Subsequently, the application of kinetics has provided a more easily quantifiable assessment. For example, the nitrogen mineralisation potential (N_0) of Stanford & Smith (1972) can be used to derive a value for the pool of active N, which may vary from 5% to 40% of the total N. Paul and Juma (1981), with a combination of tracer and modelling techniques, indicated that biomass, active, stabilised and old N fractions constituted 4%, 10%, 36% and 50%, respectively, of the total organic N. The half-life values (years) for decomposition were 0.475, 1.48, 27 and 600, respectively. The likely 36% that is stabilised N with a half-life of 27 years can provide a large continuing source of slowly available N, even with a low rate of decomposition, because of its magnitude (Greenwood, 1986).

For tillage soils in Ireland, measurements of microbial biomass and N_0 have been used as an estimate of labile N, which approximates 15% of the total N in the 0-20 cm depth (Herlihy and O'Keeffe, 1983), although this proportion may decline over time. This value greatly exceeds the annual release of Nmin. It is comparable, however, to estimates of the active N pool in the literature, and indicative of the reserve of organic N that may readily become available. Table 1 illustrates a range of values for various relevant parameters in the 0-20 cm depth. Based on these and other data, the total labile-N pool in the 0-60 cm profile was estimated to be of the order of 2284 and 1625 kg ha^{-1} in the second and sixth years of the tillage rotation of a coarse sandy loam (Herlihy and O'Keeffe, 1983). Whereas this may appear to reflect the net balance between crop requirements and crop residues in the broad sense, sustained release is likely also to invoke the stabilised N pool, as indicated above. Over time, the annual level of Nmin, which derives from the labile organic N, also continues to decline with duration in tillage (Figure 2).

Table 1: Nitrogen mineralisation potential (N_0), microbial biomass and other properties of selected soils (from Herlihy and O'Keeffe, 1983).

Parameter	Years tillage and texture*					
	Year 2			Year 6		
	LS	CSL	L	LS	CSL	L
N_0 (kg N ha^{-1})	516	781	1007	554	543	792
N_0 (% of total N)	10.5	12.4	11.9	11.3	8.7	10.4
k, 15C (week^{-1})	0.026	0.024	0.026	0.015	0.022	0.024
$t_{1/2}$, 15C (weeks)	27	29	27	46	32	29
Organic C (%)	-	1.96	-	-	1.89	-
Biomass C (kg ha^{-1})	-	1876	-	-	1463	-
Total N (%)	-	0.22	-	-	0.22	-
Biomass N (kg ha^{-1})	-	281	-	-	218	-
Biomass N (% total)	-	4.7	-	-	3.7	-

*LS, CSL, L = loamy sand, coarse sandy loam & loam, respectively.

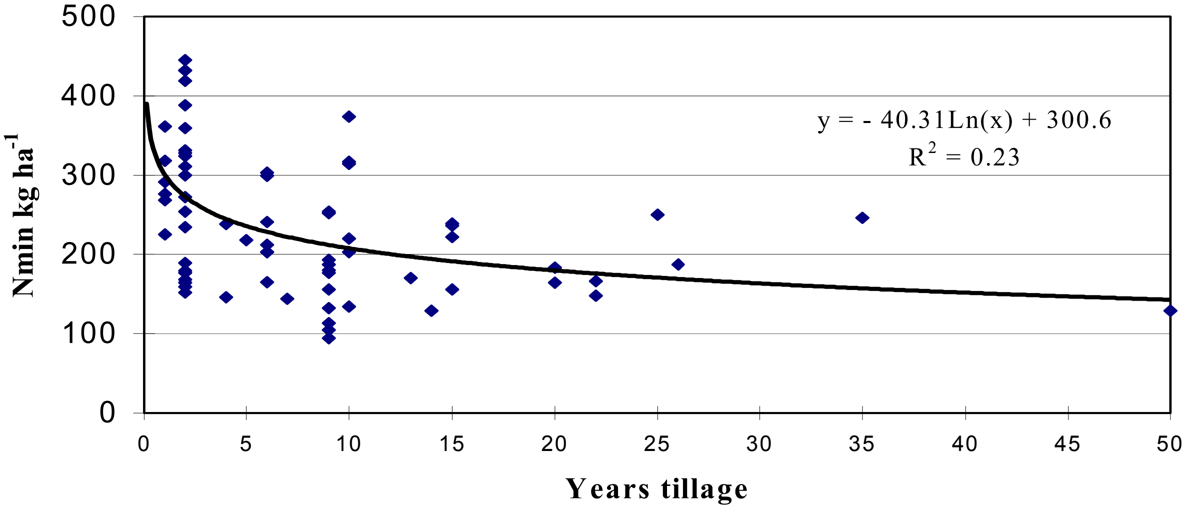

Figure 2: Variation with number of years in tillage of Nmin in June in the 0-60 cm root profile (from Herlihy and Hegarty, 2001).

Seasonal variation

In practical terms, availability of soil N in field soils is driven by environmental factors, such as temperature and soil moisture, and their influence on biological activity throughout the growing season. In Ireland, the pattern of seasonal accumulation of Nmin illustrates the relevance of N supply in relation to development of the crop, with peak levels under cropping at about the end of June. Its distribution is, therefore, better matched to crops such as sugar beet where demand is late rather than early in the spring. Peaks in Nmin in spring and autumn, and troughs in summer, have been noted in fallow soils under controlled conditions (Herlihy, 1979a), and in response to temperature fluctuations. Because of its variable nature, there is little reason to expect a consistent seasonal pattern in Nmin, and a somewhat different progression has been observed in other work (Nunan *et al.*, 2000), which had variable success in the attribution of episodes of net N mineralisation to changes in biomass or other metabolic activity.

Others have suggested that most mineralisation occurs in autumn when soils are still warm and wetting up (Johnston and Jenkinson, 1989). This opinion may reflect the relative limitation of soil moisture in different environments, but also likely reflects the more immediate source of the labile N. The trough in Nmin that has been observed in fallow soils between spring and autumn (Herlihy, 1979a) may be attributable to immobilisation of Nmin, due to a shift in the balance between decomposable C and N in the biologically active pool and/or to losses, gaseous or otherwise. Some substantiation of events underlying such variation is evident in the mineralisation process *per se* observed at defined intervals in controlled incubations

(Table 2), insofar as it demonstrates immobilisation and, certainly, minimal net mineralisation broadly in the phase in which troughs in Nmin have been observed. The timing of the maximum value is consistent with significant end-of-season release of Nmin, which also coincides with the highest seasonal levels of bacteria and actinomycetes in August-September observed in other studies (Herlihy, 1973). The complexity and implications of these results for the availability of soil N and its prediction have been accepted by others (Greenwood, 1986).

Table 2: Net N mineralisation (10-day incubation) in samples of soils stored at ambient temperature and field capacity (Herlihy, 1979a).

Soil	Sampling date									l.s.d.
texture*	06/02	09/03	12/04	17/05	22/06	26/07	31/08	12/10	11/11	(36 df, P=0.01)
CSL	50.2	66.0	83.0	44.6	23.3	19.2	34.9	113.2	44.4	9.6
L	50.2	65.3	84.9	51.0	18.6	-26.6	31.6	83. 8	50.7	9.6
Mean	50.2	65.7	83.9	47.8	20.9	-3.7	33.2	98.5	47.5	6.8

*CSL = coarse sandy loam, L = loam.

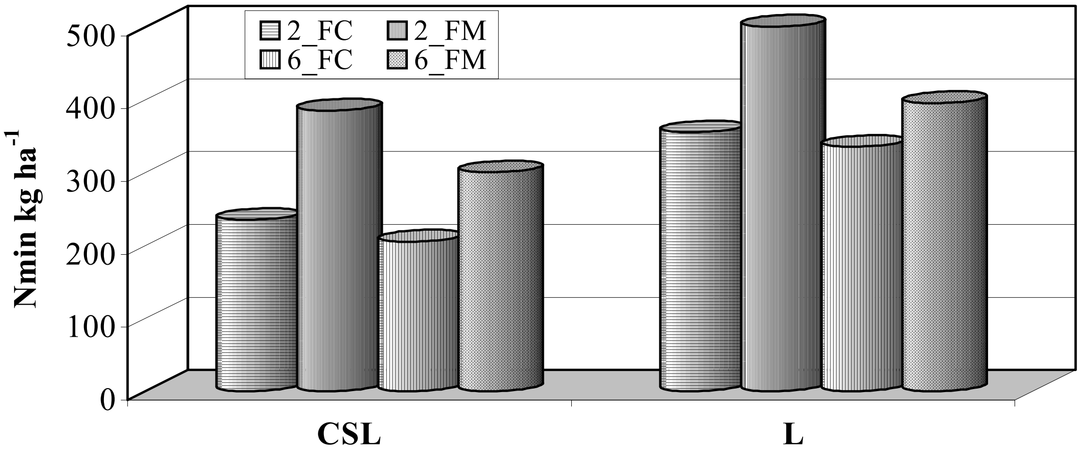

Figure 3: Nmin in soils at field capacity (FC) and fluctuating moisture (FM) in years 2 and 6 of tillage (adapted from Herlihy 1979a). CSL and L as in Table 2.

Fluctuations in soil moisture within the range of 20-100% of field capacity have been shown to stimulate levels of Nmin that exceeded the seasonal pattern observed at field capacity (Figure 3). This particular environmental stimulus to mineralisation may arise from sporadic drying and re-wetting cycles stimulating (a) lysis of N-rich microbial cells that are easily mineralised by resistant organisms and (b) increased lability of some soil organic N. The range of 20-100% field capacity used for the soils in Figure 3 is not outside the bounds of the variation observed with periodic exposure of new surfaces during spring cultivation, or of the wetting and drying cycles that occur throughout the season. The influence of complete air-drying at the ambient, noted for some other soil constituents may indicate the relevant biological and chemical changes. Thus, as illustrated in Figure 4, air-drying of soils that were in the second year of tillage after ley effected changes in the level of water-soluble carbohydrate from 68 to 92 ug C g^{-1}, water soluble nitrogen from 164 to 181 ug N g^{-1}, non-sporeforming bacteria from 280 x 10^{5} to less than 70 x 10^{5}, sporeforming bacteria from 90 x 10^{4} to 60 x 10^{4}, actinomycetes from 100 x 10^{3} to 80 x 10^{3} and fungi from 147 x 10^{3} to 107 x 10^{3}. Such sporadic variability, and the seasonal variation, epitomise some of the particular challenges to the development and application of a predictive test of N availability. Drying and re-wetting cycles have a small impact on direct release of labile N even at 40C (Appel, 1998). The trends in Figure 4, obtained at ambient temperature, indicate a greater relevance of biomass insofar as the appreciable reduction in non-sporeforming bacteria provides a source of N-rich microbial debris as substrate for renewed mineralisation. This principle has been more directly confirmed in recent studies (Herrmann and Witter, 2002).

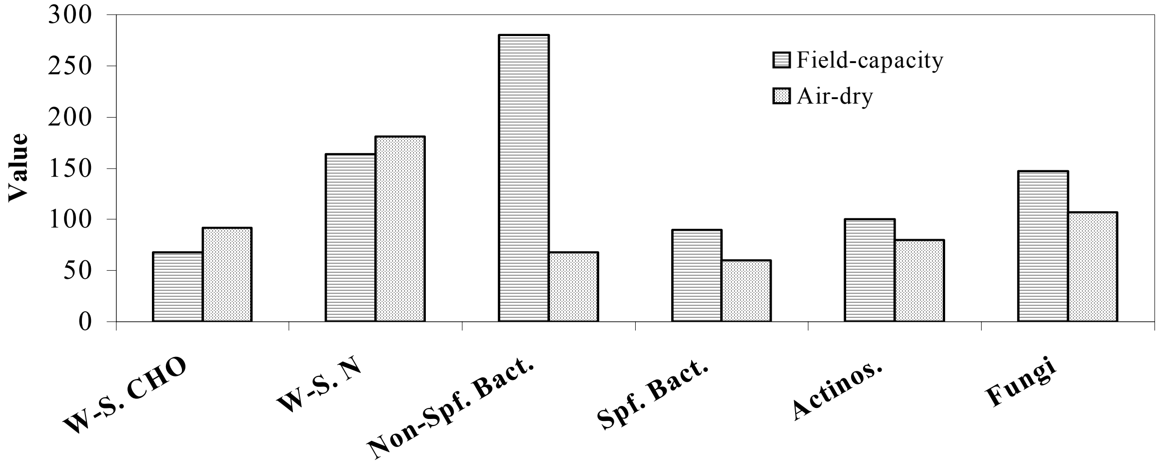

Figure 4: Changes induced in water soluble components (ug g^{-1}) and in microflora (nos. g^{-1}; see text for dilution factors) by one cycle of air-drying at the ambient of soils initially at field capacity (Herlihy, unpublished).

Soil testing for N availability

Soil testing for N availability has for long been an aspiration that, in reality, has been elusive. Its complexity is evidenced by the following:

1. Seasonal variation of mineralisation and its unpredictability (Herlihy, 1979a), and also the sporadic variation as noted above.
2. Dependence of estimates of mineralisation on date of soil sampling (Bonde *et al*., 1988; El-Haris *et al*., 1983, Herlihy, 1979a).
3. Mineralisation of N from several pools of different degrees of availability (Juma & Paul, 1984).
4. Differential susceptibility to mineralisation of residual organic N from crop production, which is distributed in all organic forms, compared with native soil N (Smith *et al*., 1978).
5. Variation in relative activities of bacteria, fungi and protozoa, both seasonally and in response to soil management (Badalucco *et al*., 1992; Herlihy, 1973) together with variation of enzyme activity independently of microbial activity (Herlihy, 1979b).

The question arises as to whether knowledge of the composition and activity of soil N enhances the application of N tests and their prediction of fertilizer N inputs for field crops. In any case, there is uncertainty about the practical application of predictive soil tests, 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 well as vertical displacement and unpredictability in the profile distribution of Nmin. As a result, recognition has arisen that simplified, empirical approaches are relevant in predicting N requirements (Dahnke and Johnson, 1990). The practice of using systems that are dominantly based on soil management/rotation implies that many tests may be unworkable or, at least, inconvenient. Any attempt at evaluation of a prediction system needs to assess both possibilities. It is notable, however, that a recent review of the topic (Follett, 2001) concluded that no generally accepted N index exists for mineralisation as such (as opposed to management-based indices).

It is ironic that, within current limits, the greater the knowledge of processes the more evident are the constraints on an analytically based, compared with a management based, prediction system. In terms of prediction of fertilizer 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 fertilizer N ultimately absorbed by the crop, as already noted. The behaviour of the crop in response to environment and management, as well as diverse attributes of different crops, equally challenge the accuracy with which soil tests may be expected to perform. Nevertheless, biological and chemical 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, typically under restricted conditions, have not always justified practical application. The most satisfactory relationships of tests with crop response 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. 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 or residual mineral N from the preceding crop, for example, has been deemed to be more practicable (Jenkinson, 1984). Management-based or rotation criteria are perhaps even more appropriate under conditions of high and variable N mineralisation in spring, such as arises in cropping systems that involve ley-arable farming.

The more relevant of the soil tests in our recent evaluation included microbial biomass, $CaCl_2$-N and Nmin, at least in principle (Herlihy and Hegarty, 2001). Microbial biomass has been found to relate better to production of mineral N than indices of any single step, because of its integrative role in mineralisation and immobilisation (Burton & McGill, 1992), and to be sensitive to change in soil management (Powlson & Jenkinson, 1981), which is attributable more to the activity of the biomass as distinct from its N content (Burton and McGill 1992). $CaCl_2$-N, 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, although it is time sensitive in terms of field sampling. Where mineralisation of organic N is its principal source, the measurement needs to coincide closely with time of maximum accumulation to provide a useful estimate of N inputs. Generally, Nmin is used more appropriately where the objective is to quantify the residual N from the previous season (Danke and Johnson, 1990). Depending on the specific circumstance and its timing, a direct profile measurement of Nmin 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, even if justified by calibration trials. In many cases alternative procedures to soil tests, based on soil management, have been used to indirectly estimate soil N availability. This has resulted in the use of broad 3-4 category index-systems, which reflect the proximate basis of such systems.

Recent research into the basis of N advice

Currently in Ireland, advice on N use for tillage crops employs a soil/crop management index-system, the basic structure of which appears to derive from an earlier UK index. A recent report attempted a systematic evaluation of several of the index components together with soil tests, using a data bank of soils in which sugar beet was the test-crop (Herlihy & Hegarty, 2001). The soil types, comprised the Clonroche, Athy, Kellistown, and Elton series and soil associations 13 and 15 as previously described (Herlihy, 1992b). Some of the specific results can be summarised as follows:

1. Nmin accumulated progressively in the 0-60 cm root 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 soils.
2. Sustainability of soil N supply was demonstrated at various stages of the tillage rotation following ley. 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 estimated as 85%, 78%, 69%, 60%, and 47%, respectively, of the one year's value. Substantial reserves of soil N were evidently released 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.
4. The best predictor of optimum fertilizer-N was a regression model that included the following terms: (a) years in tillage, (b) ratio of years in tillage/years in ley, which weighted the ley contribution relative to the stage of the tillage rotation and (c) rainfalls for the intervals April-June and July-September.
5. 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 index (Dampney, 2000). This coincidence suggests that there may be a limit to the degree of correlation attainable in large-scale field trials. Also, it implies that the values have equivalence in relative, if not absolute, terms to the inputs designated by the different UK approach. The distinction between relative and absolute terms is pertinent, because of the tendency by some to equate nutrient requirements between Ireland and the UK where soils and climate may differ substantially.
6. Sensitivity testing of the model for a range of representative values indicated the wide variation in optimum N obtainable even 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 and 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 in large-scale field experiments or farming practice.
7. Variables such as soil type or soil texture, crop yield, date of sowing, temperature, solar radiation and fertilizer-N use in ley were non-significant. These have been shown by others also to have inconsistent effects

(Greenwood, 1986, Webb and Sylvester-Bradley, 1994). Power (1981) cited a number of sources to the effect that soil organic matter and soil N contents are regulated more by the quantity than the N content of the organic materials returned to soil, including low N material such as wheat straw. Furthermore, mineralisable N has been shown to be significantly greater after cereals compared with root crops (Herlihy, 1972), although often emphasis is placed simply on the difference in residual fertilizer N from these crops in terms of the effect on a succeeding crop.

8. The results did not provide a basis for distinguishing between different soils groups, or between cut or grased 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. They may imply that parameter-values derived from experiments of limited extent cannot validly be imposed quantitatively on more extensively derived values.
9. In all, 6 biological and 8 chemical soil tests were evaluated. Combinations of soil tests and management data did not improve R^2 values. Nmin was superior to other soil tests, when combined with July-September rainfall, but inferior to the model derived from soil management criteria. 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 when Nmin provided the estimate of N availability. Overall, it was concluded that the Nmin method did not justify practical application for these soils.

The results confirmed the view that simplified, empirical, approaches are relevant in predicting N requirements, but supported other available evidence that the current N index may need to be revised. The sustainability of soil N supply suggested a greater long-term role than appears to be envisaged, currently, for the effects of leys. 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. However, both long and short term effects of leys on N mineralisation can be expected (Greenwood, 1986).

The relevance of growing season rainfall for availability of soil and fertilizer N also contrasts with the current emphasis on winter rainfall. 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, given our high annual and winter rainfalls, the relatively dominant contribution of N mineralisation, and the generally permeable nature of our arable soils. However, significant residual-fertilizer effects on malting barley from N applied to sugar beet or fodder beet have been noted in Ireland, although under rather specific conditions where winter rainfalls for the years preceding the test crop were only 63% of the then long-term average. Also, residual effects were tested in the absence of further N application, 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 from which the conclusions regarding residual effects were drawn (Gately, 1967). The probability of an even lesser residual effect is enhanced, since the optimum N input for sugar beet can be substantially less than the maximum, (Herlihy, 1992a). Even in the UK, residual effects and, consequently, the relevance of winter rainfall have been considered of most relevance on nitrate-retentive deep clay or silt soils, as opposed to lighter soils where over-winter leaching is prevalent (MAFF, 2000).

Table 3: Distribution of optimum N for sugar beet in selected rotations.

Tillage (years)	Ley (years)	Optimum N (kg ha^{-1})*
5	3	93
10	3	115
20	3	146
35	3	182
5	20	55
10	20	77
20	20	108
35	20	145

*Model-values based on mean rainfall.

It is noteworthy that the existing index system differentially assigns indices on the basis of residual effects of fertilizer-N from a wide range of previous arable crops in the rotation. However, cereals alone constitute almost 80% of the area of arable crops in Ireland (Fingleton and Cushion, 1999). Consequently, the latitude for distinguishing on the basis of previous arable crop mostly does not exist, and accuracy would be enhanced by the application of the model-based approach, as detailed elsewhere (Herlihy and Hegarty, 2001). In any case, it is likely that the assumed residual effects are overstated, as noted above. Index-1, for example, currently includes all soils that are five years, or more, in tillage. It makes no distinction for the requirements of progressively longer durations in tillage. As a result, it may under-estimate requirements for the latter, and may exceed them for the early years of index-1. These distinctions are important as the area of continuous arable cropping expands. Table 3 provides an example of the range of variation that results from the application of the proposed model output in such circumstances for sugar beet (Herlihy and Hegarty, 2001), and contrasts with a single value only that is provided by the current index system for the same mix of variables. The result is a more flexible and more balanced sequence of N inputs that reflect diverse requirements, all currently defined as one category. Evaluation of the proposed model is ongoing in order to accommodate the exponential decline in N release in succeeding years after ploughing ley.

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