Modelling and Prediction of Crop Nitrogen Requirements

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Responses to N-fertilizer have been shown, in field experiments, to depend on yield, rooting depth, weather conditions, soil type, previous cropping, total soil organic-nitrogen content, mineralization rate and the total amount of inorganic-N at the start of the growing season to the depth to which roots finally penetrate. Good correlations between one or other of these factors and fertilizer requirement have been found in nationwide trials in some countries but no such correlations have been found for any arable crop in the UK. Presumably the range of soil and weather conditions is so great that the most important factor determining response varies from field to field.

These findings have prompted British workers to study the various processes in more detail. It was hoped that such studies might lead to the discovery of quantitative relations for each of the key soil and plant processes that govern N response. Such relations could then be combined into predictive computer models for calculating the day to day increments in growth and for estimating fertilizer requirement.

Soil processes

Most UK arable soils contain at least 10,000 kg ha^{-1} of organic-N so that small changes in its rate of breakdown can make a big difference to the supply of inorganic-N. The rate depends on temperature, soil water content, pH and the type and form of the organic matter. In pockets of soil where the C/N ratio or the organic matter is high there is net immobilization of inorganic-N whereas in others where the C/N ratio is low there is a net release. Likewise there can be localized zones which are anaerobic where considerable quantities of nitrate can be lost by denitrification. Ammonium ions can be fixed by clay minerals and thereby rendered unavailable to plants. In addition ammonium ions are in pseudo equilibrium with ammonia gas which diffuses to the atmosphere above the soil. Equations have been developed for each of these processes and combined into models for calculating the net changes in inorganic-N of field soils.

Such models are complicated and involve the use of many parameters, values for some of which can only be obtained with great difficulty. Attempts have therefore been made to simplify the models without loss of predictive power.

One such model is centred around a leaching routine that divides the soil into layers and the soil solution into mobile and immobile phases. During water movement, only the mobile phase is displaced and when flow ceases an equilibrium is set up between the mobile and retained phases. For a given soil, it was found that the rate of mineralization and the rate of conversion of ammonium-N could be regarded as being dependent solely on temperature. By combining these relationships, a dynamic model was obtained which gave estimates of the distribution of inorganic-N down the soil profile in spring from the distribution in autumn and other readily available data. Using a version of the model adapted to take account of the small uptake of N by a wheat crop during winter, more than 90% of the total variance in the measured amounts of inorganic-N in the top 90 cm of ten sites could be accounted for by regression against values calculated by the model.

Plant processes

Crops differ widely in their response to added N-fertilizer. Nevertheless some fairly widely applicable equations are emerging for the total demand of the crops for nitrogen, the growth of root systems in soil and the ability of these root systems to extract inorganic nitrogen from the soil. The equations are simple and fall into three distinct groups.

Rate processes, in general, appear to be well described by diminishing returns equations of the type

$$\frac{1}{y} = \frac{m_1}{x} + c_1 \qquad /1/$$

where y and x are the variables and m and c are constants. Equations of this type defined the dependence of rate of dry matter increase on leaf area index, plant dry weight, radiation intensity and N% in the plant dry matter. They also appear to govern the dependence of the rate of ion uptake on the concentration of ions at the root surface. If an additional term, say $/m\frac{1}{2}/$ is added then the equation is a close approximation to the law of the minimum and has given a good representation of the combined effects of two independent factors on the rates of growth.

The distribution of carbon and nitrogen within plants appear to be well defined by equations of the form

$$\ln y = m_2 \ln x - m\frac{1}{2} \,.\, \text{Time} + c_2 \qquad /2/$$

where y and x are variables and m_2, $m\frac{1}{2}$ and c_2 are constants. Equations of this type have been deduced to define

1. The relation between the total weight of protein and the total weight of nitrogen-free organic material on crops that have been grown with just sufficient N to permit maximum growth rate. It defines the N-requirement for crops of different weight.

2. The relation between root length and the weight of the above ground parts of the plant.

3. The relation between the weight of storage root and leaf weight of some root crops.

The development of roots in a uniform soil seem governed by linear relationships. Invariably the logarithm of root density declines linearly with depth from the soil surface. Also the depth of soil containing 90% of the roots or any other fixed percentage of roots has been found to increase almost in proportion to the increase in plant weight.

But perhaps of even greater significance is the finding that many of the coefficients of the equations are the same irrespective of the crop species. This is well illustrated by measurements of total plant dry weight /w t ha^{-1}/ made at intervals during the growth of six different crops receiving ample water and nutrients until the start of senescence. The rate of dry matter increase was always related to W by

$$\frac{dw}{dt} = \frac{K_2 W}{1 + W} \qquad /3/$$

and the value of K_2 varied only between 0.18 and 0.2 t ha^{-1} d^{-1} from species to species during the main growing period May to September when the average monthly radiation does not vary greatly. It is also well illustrated by measurements of N% in the plant dry matter at harvest of 18 different vegetable crops that had been grown with the optimum levels of N-fertilizer. The N% of these different crops all fitted closely about the same curve when plotted against total plant dry weight per unit area. In addition the depth of soil containing 90% of the roots increased by approximately the same distances, 10 cm, for each tonne increase in dry weight of four widely different non-leguminous species when grown in the same experiment.

Current evidence suggests that much of the difference between the responsiveness of the various crops to N-fertilizer may be attributed to differences in the sensitivity of growth to the N% falling below that needed for maximum growth rate. Experiments have been carried out to characterize this aspect of response for a wide range of crop species.

Dynamic models

Equations such as those described in previous sections have been combined to form dynamic models for calculating the day to day changes in inorganic N down the profile, increases in N uptake and increases in plant dry weight. The models can be modified for use with different crops by altering values of some parameters.

Inputs of one model are

1. The distribution of inorganic-N down the profile at the start of growth.
2. The time and level of fertilizer application.
3. The time of planting.
4. The daily rainfall and evapotranspiration.
5. The maximum yield.

It is being tested against the results of well monitored N-fertilizer experiments on widely different sites and with widely different crops. So far comparisons have been made with sugar beet and potatoes, and quite good agreement has been obtained between calculated and measured values of the growth of total plant dry matter. N% in the dry matter and inorganic-N in the top metre of soil at intervals during growth on plants receiving different levels of N-fertilizer.

The intention is to develop the models so that growers can run them on their own microcomputers with their standard field records and weather data as inputs.

Rapid soil and plant tests

The usefulness of such models could be greatly increased by providing information about the nitrate levels in the soil or plant or total crop dry weight at some time during growth. In an attempt to meet this need and also to provide the basis of an independent method of estimating N-fertilizer requirement, rapid tests have been developed for estimating the nitrate status of plants and soils. From measurements made at a given time during growth, we are developing methods of forecasting how much nitrogen top-dressing is needed and when it should be applied. In the future we anticipate that the present chemical methods will be replaced by micro-electrode procedures. It also seems likely that methods based on remote sensing multispectral scanners will be developed for monitoring growth and nitrogen status of crops.