Section

3

3. Nutrient Management Plans

Food safety assurance schemes are strongly focussed on chemical safety in the supply-chain and in food production. Particular attention is paid to documenting responsible fertiliser use in the production of food or fibre. Nutrient management plans, that use nutrient budgeting, are being accepted as an appropriate method to audit fertiliser use (recommendations) for food safety assurance and leaves an appropriate auditable record with the farmer. Similarly, nutrient budgeting is the preferred tool for evaluating the environmental impact of farming practices, which include fertiliser use.

Within New Zealand, the Overseer model is the preferred method with which to audit nutrient management practices for adherence to the Code of Practice for Nutrient Management. The link to this document is also available on the Fertiliser Association of New Zealand website (fertiliser.org.nz). It is important to be familiar with the Code of Practice for Nutrient Management, particularly the General section, the Objectives page and the page on Evidence that environmental risks have been assessed. Many Regional Councils also require Overseer for auditing the estimated loss of nitrogen (N) and phosphorus (P) in farm runoff and drainage.

3.1 Overseer

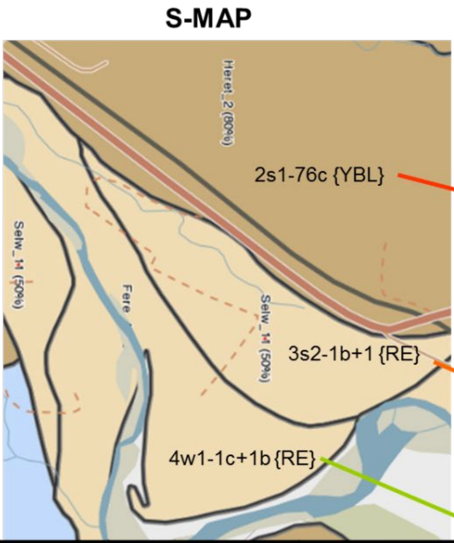
When assessing a farm using Overseer, it is important to understand the inputs that are required to produce correct reports for that particular farm. This is because there are a number of inputs for the farm system that can have a large impact on the outputs provided by the model. If you have limited experience with using Overseer, please download the Overseer User Guide, which can be accessed from the Overseer model. Additional information about Overseer can also be obtained from the Overseer web site (overseer.org.nz). For this course you will using the Education version of Overseer (edu.overseer.org.nz).

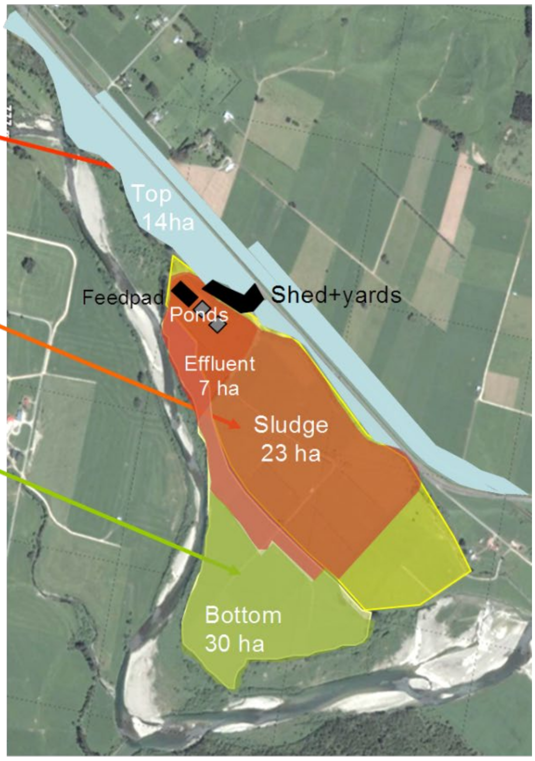
The following section discusses some aspects of data input in to Overseer that require careful consideration. Complete this section before you begin to enter the dairy farm case study information into Overseer. This will help with assessing the Overseer reports, including the nutrient budgets, and writing the case study report.

The following information is provided to assist you with grouping farm paddocks into blocks of similar soil characteristics and management, that can form the land management units simulated by Overseer.

Step 1. Before visiting a farm, locate the farm in Overseer and determine whether the SMap soil information is available for the farm. If there isn't SMap soil information available for the farm in Overseer, check with the farmer whether they have any soil maps or other soils information for the farm. There may be other soil recourses available, depending on the region the farm is in. Also, be familiar with the information required by Overseer and Overseer User Guide (available at overseer.org.nz), which can be used to guide what questions you need to ask the farmer.

Step 2. A visit to the farm is essential to ground truth the soil boundaries and obtain information on how the paddocks on the farm are managed differently.





Block	LUC	S-MAP	Soil type (Order)
Top block (14ha)	2s1	Heret 2a.1	Heretaunga Silt Loam (Brown soil)
Effluent block (spray +sludge) (7ha)	3s2	Selw_11c.2	Manawatu Deep silt loam (Recent soil)
Effluent block (sludge) (23ha)	3s2	Selw_11c.2	Manawatu Deep silt loam (Recent Soil)
Bottom block (30ha)	4w1	Fere_4d.1	Esk deep sand (Recent soil)

Figure 3.1.1. Assembling the soil resource and block management information for a dairy farm in the Horizons Region. This was done using SMAP and Land Resource Inventory online data bases (see text) and information on paddock management from the farmer.

On the all-pasture dairy farm, illustrated in Figure 3.1.1, the management differences are mostly associated with the paddocks that receive farm dairy and feed pad effluent and the paddocks that receive sludge from the effluent holding ponds. The farmer holds soil test information that confirms that the soil on the upper terrace (10 m above river level), "Top block", is a Brown soil with medium anion sorption capacity (ASC), whereas, the soils of the middle terrace (3-4 m above river level) have a low ASC. A farm walk with a spade and a soil corer confirms the soils are different and show different texture and drainage status (Figure 3.1.2).

Block	LUC	S-MAP	Soil type (Order)
Top block (14ha)	2s1	Heret 2a.1	Heretaunga Silt Loam (Brown soil)
Effluent block (spray +sludge) (7ha)	3s2	Selw_11c.2	Manawatu Deep silt loam (Recent soil)
Effluent block (sludge) (23ha)	3s2	Selw_11c.2	Manawatu Deep silt loam (Recent Soil)
Bottom block (30ha)	4w1	Fere_4d.1	Esk deep sand (Recent soil)

Figure 3.1.2. A farm walk to ground truth the soils and their drainage status. Well drained Heretaunga silt loam (a Brown soil with medium % ASC). The Manawatu deep silt loam (a Recent soil) shows signs of temporary gleying in the topsoil probably from treading damage when wet.

On this dairy farm the farmer does not have any other management practices that would cause nutrient flows to and from each paddock to differ. For example, pasture renovation and surplus pasture conservation is rotated around all areas. No fodder crops are grown on farm.

While visiting the farm, information on the purchase of supplements and fertilisers and where and when they are fed or applied, respectively, can be obtained. All supplements are fed on the feed pad and the fertiliser use differs based on soil type and whether effluents or solids are applied to a paddock. On this basis we are able to overlay the farm photograph with our concept of the nutrient inputs, transfers by the grazing cow (ingestion and excretion) and transfers by effluent or sludge application (Figure 3.1.3).

This visual concept helps us confirm that there are 4 different management blocks on this farm. The different blocks (or indicator paddocks within each management block) should be soil sampled separately. Once the soil test information has returned from the laboratory, you are ready to complete the Overseer analysis of this farm.

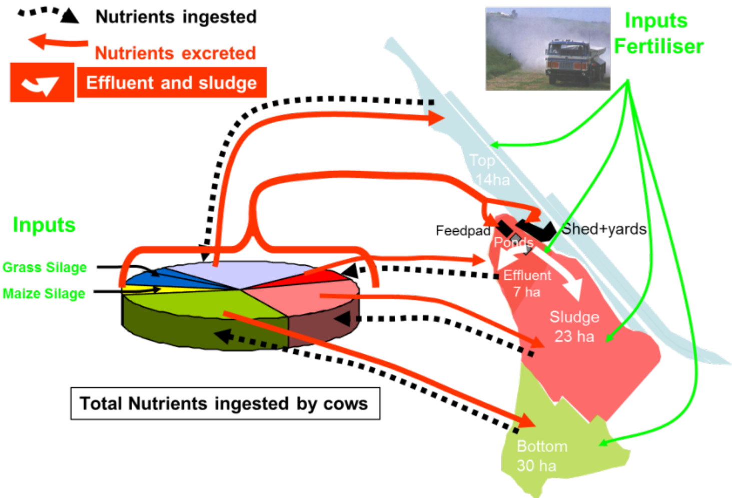


Figure 3.1.3. A visual concept of the nutrient inputs, transfers by the grazing cow (ingestion and excretion) and transfers by effluent or sludge application.

The resources and management on this farm are not complex. When assembling data for an Overseer analysis on some farms, there may well be a more complex arrangement of resources and management. This could require the formation of different management blocks.
Key resource differences to look for are:
i. The land unit - elevation, rainfall, topography, soil order, texture, profile drainage, artificial drainage.
ii. Land uses - pasture, pasture conservation, grazing animal type (or cut and carry) and stocking rate. Crop type and trees.
iii. Nutrient or water Management system - i.e. type of effluent and/or sludge applied, irrigation applied, and fertiliser type and application rate. Where supplementary feed is fed to grazing animals.

Nitrogen Fertiliser

From an environmental aspect, when adding and removing N fertiliser it is important to understand what impact these changes will have on the results in Overseer. By removing/adding N fertiliser you should see a reduction/increase in N losses to water and/or atmosphere on a block and farm scale. However, the degree of change is dependent on some variables, these are; size of the block compared to the whole farm; amount of N being removed, or added, the timing of the fertiliser and soil type on the block, or farm.

Reducing N fertiliser application rates can reduce N losses, as there will be less N cycling in the farm system that has potential to be lost. Whereas increasing the rate should have the opposite effect. However, there are certain periods of the year where the addition/reduction of N fertiliser will have a larger effect on Overseer outputs. These are the high-risk months for drainage; the winter months of May, June and July. Applications during these months could increase N losses more dramatically when compared to other months of the year. Similarly, removal of applications during this period will have the greatest effect on reducing N losses.

Soil type on a farm block will also affect the N outputs reported by Overseer from a reduction/addition of N fertiliser. For a given rate of N fertiliser applied, a free draining soil will have higher N losses to water compared with a poorly drained soil (assuming all other factors are the same). In addition, poorly drained soils promote denitrification and have higher losses of N to the atmosphere, so less N is available for loss to water. When taking into account the removal/addition of N fertiliser and how the above variables can affect the degree and type of N losses found in the Overseer outputs, it is also just as important to remember what outputs are not affected. The most important output from Overseer that is not affected, is the estimated pasture production. **While changes in N fertiliser may increase/decrease N losses, it will not have any effect on pasture production in the Overseer model. This is because pasture production in the model is estimated from animal requirements not soil fertility status.** So while you may be able to show a large reduction in N losses on a farm by removing N fertiliser, you need to make assumptions of what the impact will be on the farm system. You will have to make a judgement based on the default growth response to applied N (kg DM grown per kg N applied). Does the quantity of N you wish to remove grow significant amounts of dry matter? If so, when withdrawing that N, you will need to lower stock numbers, or animal weight gains, or milk yields. The alternative is to replace N with supplementary feed. All changes in Overseer should be realistic and supported with well explained assumptions.

Supplementary Feed

There are two main supplementary feed types inputted into Overseer; imported supplement and farm-grown supplement. Imported supplement refers to the feed products that are produced off the farm and usually fed out in the milking shed, on a feed pad or on blocks. Farm grown supplementary feed is harvested from pasture or crops grown on the farm. Therefore, imported supplements are a source of additional feed and can allow for an increase in production, whereas farm-grown supplements are often taken from during pasture renovation and generally have less impact on increased nutrient inputs and farm productivity.

Imported supplementary feed can be brought on farm to replace pasture production that is lost through removal of N fertiliser or to increase milk production. When creating a new farm scenario that involves importing additional supplementary feed, an assumption needs to be made about the influence of that supplementary feed on the farm system (e.g. increased milksolids production, stocking rate) and expected changes need to be made manually. [**N.B If you are not an expert in the farming system being studied, you are advised to consult an expert before making such changes.** Helpful feeding guides for dairy cattle can be found on the DairyNZ website]. If these changes are not made, then the quantity of pasture production estimated by Overseer will automatically decrease, as it will assume that new energy supplied through the imported supplement replaces some of the energy previously provided by pasture. Assumptions about the influence of any decreases in imported supplementary feed need also be accounted for by making the corresponding changes in Overseer.

A change in the type of supplementary feed imported can affect the amount of N being leached from the soil profile due to the N content of the feed. Changing from pasture silage, which is a high N feed, to maize silage, which is a low N feed, will reduce the amount of N being brought into the farm system. Therefore, this change would also reduce the amount of N cycling in the farm system and potentially leached to water.

Cropping within the pastoral system

The sowing of fodder crops in dairy systems often requires conventional cultivation of long term pasture, which has built up a large store of soil organic matter and, therefore, organic N. Cultivation results in the mineralisation of organic N which is converted to nitrate. Cultivation is usually followed by a fallow period or the planting of crop seeds that have a low requirement for N until their roots establish. If these events coincide with drainage, then nitrate leaching losses can be high. Avoiding fallow periods and if possible, timing cultivation and early crop growth to avoid drainage periods, can reduce nitrate losses. Cut and carrying crop to a feed pad, or other areas of the farm, will remove nutrients from the block and reduce the amount of N prone to leaching.

Fodder crops, which are grazed in-situ, are usually heavily stocked for short periods of time. Animal management that reduces the concentration or the number of urine deposits, particularly in autumn and winter, can be effective at reducing nitrate leaching when drainage occurs. Stock class can influence the urinary N load deposited and, therefore, the risk of N leaching.

Wet soils are prone to animal treading damage, which compact soils and reduce crop growth. Saturated soils are low in oxygen and under these conditions soil nitrate can be denitrified to nitrous oxide gas and then N gas that enters the atmosphere. Standing animals off saturated soils can reduce soil damage and N loss to the atmosphere.

The following summarises the key mitigation strategies that can be used to reduce the risk of N loss with fodder crops:

- Avoid cultivating long-term pasture just prior to drainage. Consider alternative crops that can be sown outside of the drainage period.
- Do not leave cultivated soil fallow, especially during drainage periods, maintain cover and crop N uptake during the drainage period.
- Reduce concentrated urine deposition, particularly in autumn and winter.
- Consider grazing crops with a lower stocking rates and/or a class of animals that deposit smaller urine spots.
- Avoid grazing when soils are saturated, to reduce nitrous oxide and N gas emissions.

Feed pads and wintering pads

Standing cows off-paddock is a practice that dairy farmers use, particularly on poorly drained soils, to reduce treading damage to pastures and/or reduce losses of nutrients and contaminants in surface runoff and drainage. Wet soil conditions prone to treading damage mostly occur in winter and spring, whereas, late-summer and autumn are likely to be the most effective seasons to stand cows off pasture to reduce N loss to water, as this reduces the return of N in urine spots in the period preceding the commencement of the drainage season.

Careful consideration needs to be given to any decisions relating to the introduction and use of standoff facilities on a farm due to the implications for cost (capital and maintenance) and creation of new management challenges, such as effluent management. When entering information about standoff structures it is important to ensure the information relating to the number of cows using the facility and the months and durations of use are as accurate as possible. This is because these factors influence N losses to water and the quantity of effluent generated on farm.

The choice of structure type will depend on how it is going to be used. A 'feed pad' is a hard surface area (usually concrete) where dairy cows typically spend short durations (1-2 hours/day) during certain months of the lactation season, before or after milking, where they receive supplementary feed. A 'wintering pad' or 'animal shelter' are specially built areas that enable stock to be stood off pasture for extended periods (i.e. days, weeks or months at a time). Because of the long duration that stock can spend on wintering pads it is important that they have suitable areas to lie down comfortably (e.g. bark surface or free stalls).

Assignment A – Dairy Case Study

The dairy case study information to allow you to complete Assignment A, has been provided as a separate document from this study guide. An example report format has also been provided with the case study information, and is intended to guide you when presenting Assignment A as a professional report to a farming client. Your report should be clear, concise, and cover all the sections suggested in the example format. Once completed, mail the completed assignment to the course administrator by the due date.

3.2 Sustainable Nitrogen Management in Arable Systems

Introduction

Nitrogen (N) is generally considered to be the most important nutrient required for cereal and vegetable crop production. Nitrogen fertiliser use in cropping in New Zealand gradually increased in the 1970's, and escalated when locally produced Petrochem urea entered the market in the early 1980's (Craighead and Clark, 1989). With the increased use of N fertilisers, farmers became more interested in techniques that could improve the prediction of fertiliser N requirements of crops. An ability to better assess fertiliser N requirements will not only help to improve economic returns from crops, but also aid in avoiding environmental pollution of groundwater and surface water with nitrate. Before we can proceed with this topic it is necessary to refresh your knowledge of the N cycle in arable systems.

Section 3.2 is comprised of 5 modules:

3.2.1 Nitrogen cycle for arable crops: a refresher
Designed to revisit and extend your knowledge of the N cycle with particular emphasis on the processes occurring in arable systems.

3.2.2 Predicting fertiliser N requirements of arable crops
An introduction to the historical and current methods for predicting the N requirements of arable crops.

3.2.3 Winter nitrate leaching from vegetable production.
A discussion of New Zealand data on nitrate leaching from vegetable crops, followed by an introduction to crop management strategies useful in reducing N leaching losses.

Assignment B – Arable Case Study

The arable case study information, for you to use to complete Assignment B, has been provided as a separate document from this study guide. An example report format has also been provided with the case study information, and is intended to guide you when presenting Assignment B as a professional report to a farming client. Your report should be clear, concise, and cover at least all the important sections as in the example format. Mail the completed assignment to the course administrator.

3.2.1 Nitrogen cycle for arable crops: a refresher

Key Learning Objectives

After studying this section you should be able to:

1. Describe the major transformations of N in the N cycle and the key differences between the N cycle in arable and grazed pasture systems
2. Explain how differences in soil tillage, crop and residue management, and climate influence crop uptake of soil and fertiliser N.
3. Explain what factors influence the leaching loss of soil and fertiliser N from arable soils.

Nitrogen cycle

To develop an advanced understanding of the N cycle in arable systems we need to refresh our knowledge of the forms of N in soils, their transformations between soil forms and gains and losses of N from the soil.

Fill in the following table providing definitions of the terms used.

Term	Definition including the change of N form where appropriate
Symbiotic N fixation	e.g. The transformation (reduction) of N_2 gas to transient NH_3 and then assimilation into amino acids by legume root nodule bacteria such as rhizobium sp.
Mineralisation	
Mineral N	
Nitrification	
Immobilisation	
Denitrification	
Volatilisation	

Nitrogen cycle for arable crops

The N demand of a crop plant is met through uptake of nitrate (NO_3^-) or ammonium (NH_4^+) ions from the soil solution (Figure 3.2.1.1). The nitrate and ammonium concentrations are replenished by the decomposition of organic N. The sources of organic N are the soil organic matter, previous crop residues and organic manures or composts. If the soil N supply from the rate of organic matter decomposition does not meet crop demand, then N fertilisers can be used to directly supplement the nitrate or ammonium pools (termed soil mineral N).

Nitrogen loss processes (nitrate leaching, ammonia volatilisation and denitrification), N immobilisation processes, (temperature limited decomposition and incorporation of soil mineral N back into soil organic matter, immobilisation) and plant rooting depth prevent the crop from recovering all the mineral N in the soil profile. Thus, plant N uptake can be considered to result from the partial recovery of different soil N sources.

$$\text{Plant N uptake} = (N_s R_s) + (N_m R_m) + (N_f R_f) \qquad \text{(Eq.1)}$$

Where:

N_s = Soil mineral N at 0-60 cm depth at planting

R_s = Recovery fraction of soil mineral N at planting

N_m = Net mineralised N (from soil organic matter and previous crop residue)

R_m = Recovery fraction of N mineralised during crop growth

N_f = Fertiliser N input

R_f = Recovery fraction of fertiliser N

In all soils, 95% of all soil N is held in the soil organic matter thus the rate of soil organic matter synthesis and decomposition has considerable control over the amount and timing of soil N availability to crops.

The key differences between the N cycle you have studied for pastoral soils and the N cycle for arable crops (Figure 3.2.1.1) in chronological order are:

- The major impact that cultivation practices have on the decomposition of soil organic matter and the mineralisation of soil organic N to ammonium and nitrate ions
- The lack of N input through biological N fixation (for most crops).
- The large amount of N that is taken up by the crop and not recycled during a growing season.
- The large amount of N that can be removed at harvest.
- The reduction in the soil organic matter and organic N pool size as the number of years the soil has been cultivated and cropped increases.

Thus, an understanding of soil organic matter dynamics in arable systems is essential to understand the N cycle.

The important influence of soil organic matter dynamics on soil N supply

Most of our cropping systems in New Zealand are operated with pasture rotations, on relatively young (by world standards) soils of loessial, alluvial and volcanic origin. The main soils, used for cereal and potato cropping are Pallic Soils (Yellow-grey earths) and Recent alluvial soils in the central and eastern North Island and eastern South Island. Maize, potato, onion and vegetable growing also extends to Allophanic Soils (Yellow-brown loams), Brown granular loams and Red-loams in the North Island. Small areas of basaltic tuff soils are used for cropping around Timaru. Many of the soils of volcanic origin have very high organic matter contents (7-12 % organic carbon by weight) under the initial permanent pasture. Such high organic matter contents are unique characters of New Zealand arable soils of volcanic origin compared to older arable soils in other regions of the world.

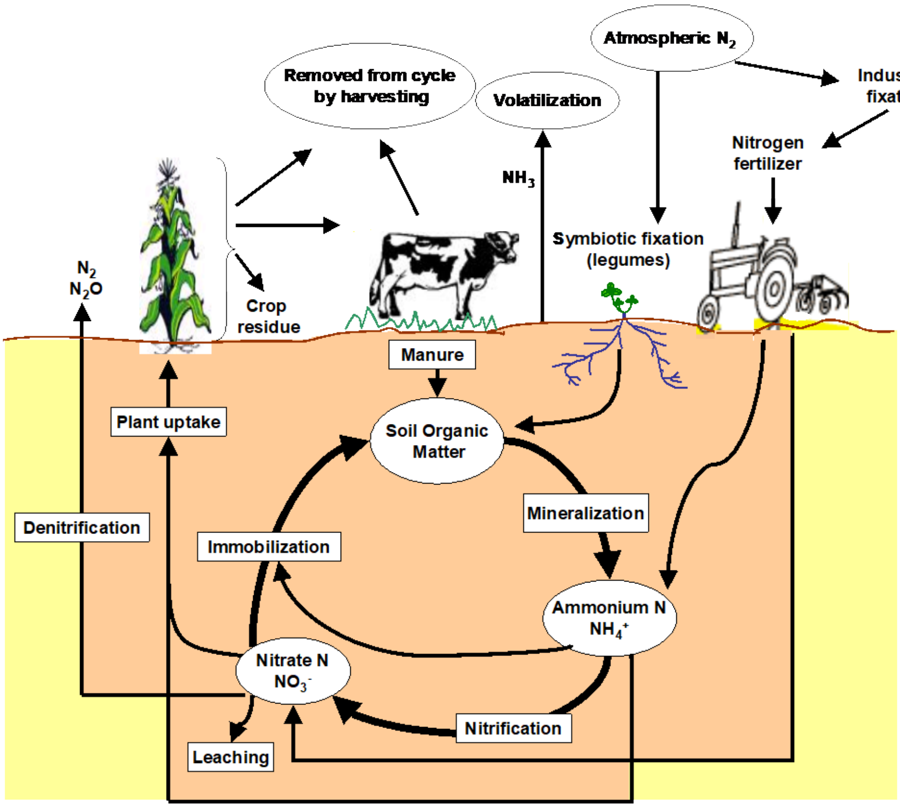


Figure 3.2.1.1 A simple N cycle for arable cropping

Cultivation practices to grow crops (cropping) involve many different types of tillage equipment (from mouldboard plough to direct drill) but they have a common purpose, to remove the competition of previous plant cover from the seeded or planted area and to prepare soil tilth suitable for the germinating seed (or seedling), in the whole or part of the soil surface.

Continuous cultivation of soil by full tillage and harvesting of crops eventually leads to a decline in soil fertility mainly because continuous cultivation accelerates organic matter decomposition. With low organic matter contents soils (particularly Pallic and Recent alluvial silt loams) lose their natural tilth and become blocky and massive in structure making seed bed preparation difficult. Reduced organic matter content leads to lower soil N supply. This has been recognised for centuries by arable farmers, and the more prudent farmers spell the land and use restorative crops or pastures in their crop rotations to slow this decline or even reverse it. Let's examine the processes involved in organic matter synthesis and decomposition in soils.

Soil organic matter decomposition

Soil organic matter content is a very dynamic characteristic of soils and at any one time, the amount present in the topsoils is influenced by:

- **the amount of recently added organic residues**
  - organic matter decreases as the amount of crop removed increases
  - organic matter decreases with removal/burning of crop residues
  - organic matter increases with increased residues from previous crop or pasture phase

- **the amount of existing soil organic matter (older humus fractions)**

- **the fraction of residues and soil organic matter decomposing annually**
  - decomposition of organic matter increases in warmer moist soil conditions, as this stimulates microbial processes.
  - decomposition of organic matter increases with tillage, as the introduction of oxygen increases the rate of organic matter decomposition.

Building soil organic matter in pasture soils

Increased soil organic matter increases the soil's reserve of N and S and P in organic residues, which generally improves soil fertility. Since most New Zealand soils are fine textured silt loams the increased organic matter plays an important role in forming larger aggregates of the silt sized particles; this maintains a topsoil structure that allows free drainage and aeration. This build-up of organic matter occurs because organic matter inputs through pasture litter, dung and senescing roots are large and they enter a relatively undisturbed soil profile, in which decomposition is probably limited by substrate accessibility to the decomposer organisms (bacteria and fungi). This is partly due to the formation of the aggregates themselves, which tend to protect the organic matter that binds them from decomposer organisms and can limit the diffusion of oxygen to the site of decomposition (Figure 3.2.1.2).

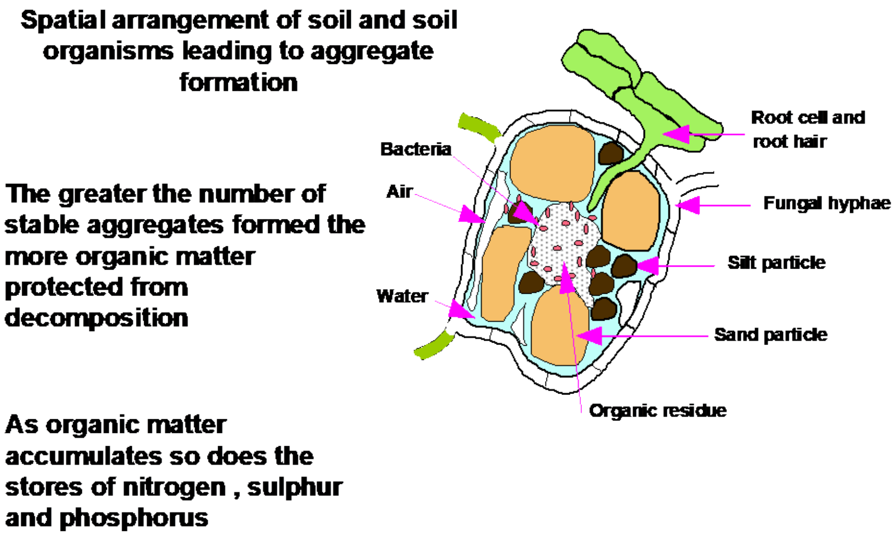


Figure 3.2.1.2 A concept to explain immobilisation of nutrients in soil organic matter protected from decomposition within water stable aggregates.

Water stable aggregate formation as shown in Figure 3.2.1.2 probably occurs as follows. Root exudates and polysaccharide gums produced by decomposing bacteria cause soil silt and sand sized particles to adhere to each other. Root hairs remove water from the aggregate causing decomposition to stop and the gums to set with hydrophobic groups to pointing outwards to the dry exterior. On rewetting of the soil the hydrophobic exterior of the aggregate prevents it rewetting. Decomposition of organic matter cannot continue in the water stable aggregate.

Examine the data presented in Figure 3.2.1.3 which shows some European data on how the percentage of the soil in larger water stable aggregates increases with time if an old arable soil is sown down to permanent pasture (Grass sown 1948). If the amount of organic matter protected by aggregates increases so does the soils store of organic N, S and P.

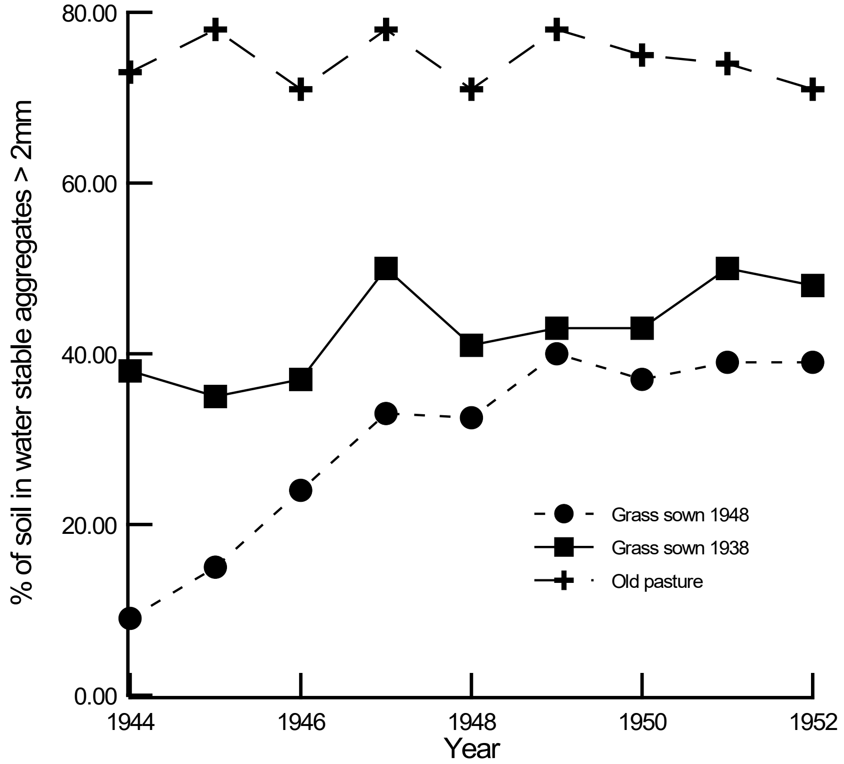


Figure 3.2.1.3 Changes in the aggregation of a clay loam under grassland of different ages. (Data from Low, 1955)

Organic matter mining under continuous cultivation

If a cropping regime is imposed on a soil under pasture the influence of the cultivation practice on soil properties will vary with the nature, intensity and frequency of:

1. cultivation and tillage
2. crop and product removals
3. erosion and leaching processes
4. manure and fertiliser application

1. Cultivation and tillage

The mechanical stress on the soil caused by tillage equipment (from hand tillage with spade and rake to the modern farming practice with a "one-pass system" using a plough, discs, rotatiller and Cambridge roll, all pulled by one tractor) physically breaks water stable aggregates and exposes previously protected organic matter to decomposers. Consequently, decomposition rates increase, more carbon is lost as CO_2, the soil organic matter content declines and so does the number of water stable aggregates (Figure 3.2.1.4).

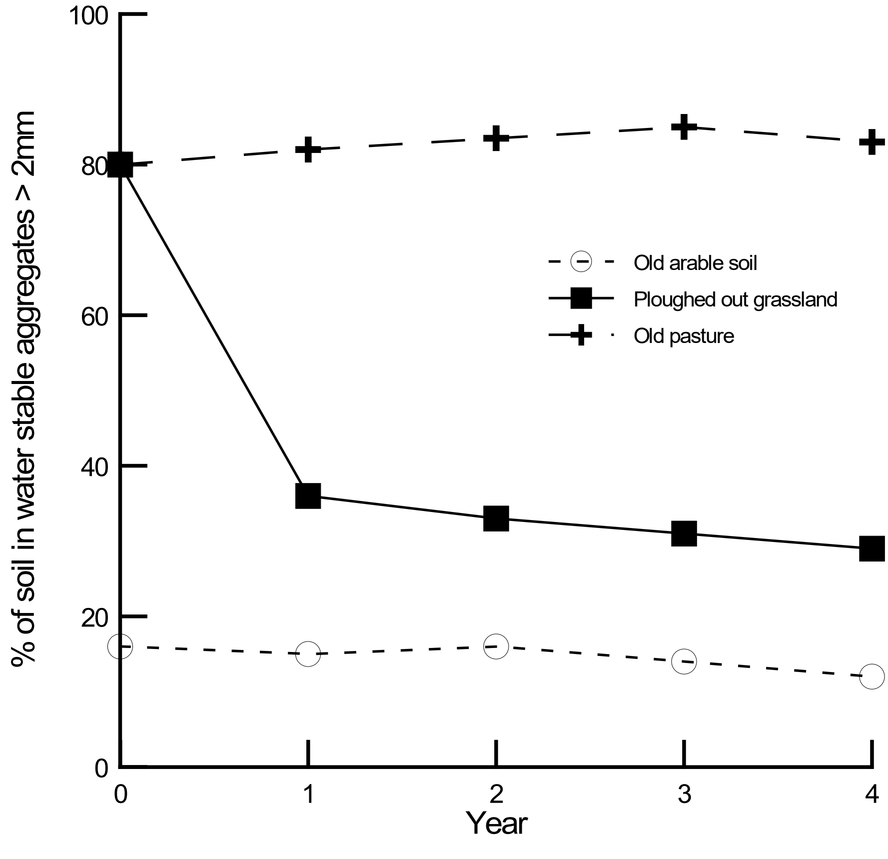


Figure 3.2.1.4 The effect of cultivation on the percentage of the soil in water stable aggregates > 2 mm.

2. Crop and product removals

Under cropping regimes the amounts of organic matter returned to the soil each year can be low relative to pasture soils, partly due to the removal of the crop (complete removal of grain and straw = high harvest index) and partly because many crops expend less photosynthate on root growth than pasture grasses. For the organic matter content of the soil to be maintained the decomposed crop residue, must be greater than the annual decomposition loss of soil organic matter. See example in point 3 below.

3. Erosion and leaching processes

The involvement of organic matter in soil structure helps to maintain high porosity in soils allowing adequate drainage and aeration. Reduction in soil organic matter and the consequent deterioration in soil structure causes major tillage problems and crop yield reductions on silt loam textured soils. Adequate pore space for drainage and aeration can only be achieved in these soils if the finer silt and clay particles are held in larger aggregates by soil organic matter. As the organic matter content declines, the number of water stable aggregates decreases allowing rainfall impact to cause aggregate breakdown. The fine silt and clay particles from the ruptured aggregates tend to form a thin unstructured layer on the soil surface (crusting). This crust has low infiltration rates causing more run off to occur during heavy rain. Thus, reduced organic matter content reduces water infiltration rates into soil surfaces and decreases the hydraulic conductivity (drainage) of the bulk soil. This in turn reduces aeration in the cropped soil. Tillage causes significant earthworm death. Decreased pore space also results from decreased earthworm activity in cultivated soils.

Greater runoff volumes remove more silt, clay and organic matter, the soil particle size fractions that have the largest specific surface area and the largest nutrient content per unit weight. Wind and water erosion may account for as much of the organic matter decline due to continuous cultivation as the increased decomposition caused by tillage.

4. Manure and fertiliser application

To increase soil organic matter content, inputs of decomposed plant and animal residues must exceed the rate of decomposition of soil humic material. Therefore, practices which influence both the input of crop residues and their rate of decomposition, can have an impact. If it is considered that approximately 2% of older soil organic matter may decompose per year, and the soil organic carbon content of the top 150 mm of soil is 90 tonnes (i.e. 6% organic carbon with a bulk density of 1 tonne/m^3), then 1.8 tonnes of organic carbon must remain as undecomposed residue each year to maintain soil organic matter content. To provide 1.8 tonnes of C as undecomposed residue, it will be necessary to add approximately 30 tonnes of organic manure (compost or crop residue) per year. This assumes that the manure or crop residue has a moisture content of 30%, the organic carbon is 50% of organic matter on a dry weight basis and that 40 % of the carbon remains after decomposition. As very few crops leave 30 tonnes of residue, soil organic matter contents of mineral soils under long-term cropping commonly decline to reach equilibrium contents of 1-2%

Impacts on soil nutrient content and N supply

Cation storage

Organic matter carries a net negative charge and contributes to the soil's cation exchange capacity (CEC). Therefore, as organic matter declines, the soil's capacity to retain and supply nutrient cations to the crop will decrease (see example for Maize cropping Table 3.2.1.1). In addition, the increased concentrations of anions (NO_3^- and SO_4^{2-}) in soil solution, derived from organic matter mineralisation, lead to more cation leaching losses in aquic (where rainfall exceeds evapotranspiration) environments.

Nitrogen stored in the soil organic matter

Data on the effects of eleven years continuous maize cropping on the chemical and physical characteristics of Manawatu sandy loam (derived from recent river alluvium) and Kairanga silt loam (a gleyed soil derived from recent river alluvium) are shown in Table 3.2.1.1.

Table 3.2.1.1 The impact of continuous maize cropping on soil properties

	Manawatu sandy loam		Kairanga silt loam	
Soil property	Original pasture	11 years maize	Original pasture	11 years maize
% Organic carbon	3	1.5	7	3
Total N (mg/kg)	3800	1500	5000	3000
Cation exchange capacity (cmol charge /kg soil)	15	11	21	18
Total porosity %	58	46	64	45

Soil organic matter contents have been at least halved in the 11-year maize cropping period (Table 3.2.1.1) and this has the consequence of decreasing the soil's store of organic N, cation exchange capacity and total porosity. The decline in organic matter with time under cropping (Figure 3.2.1.5) was modelled, assuming erosion loss of soil organic carbon was negligible.

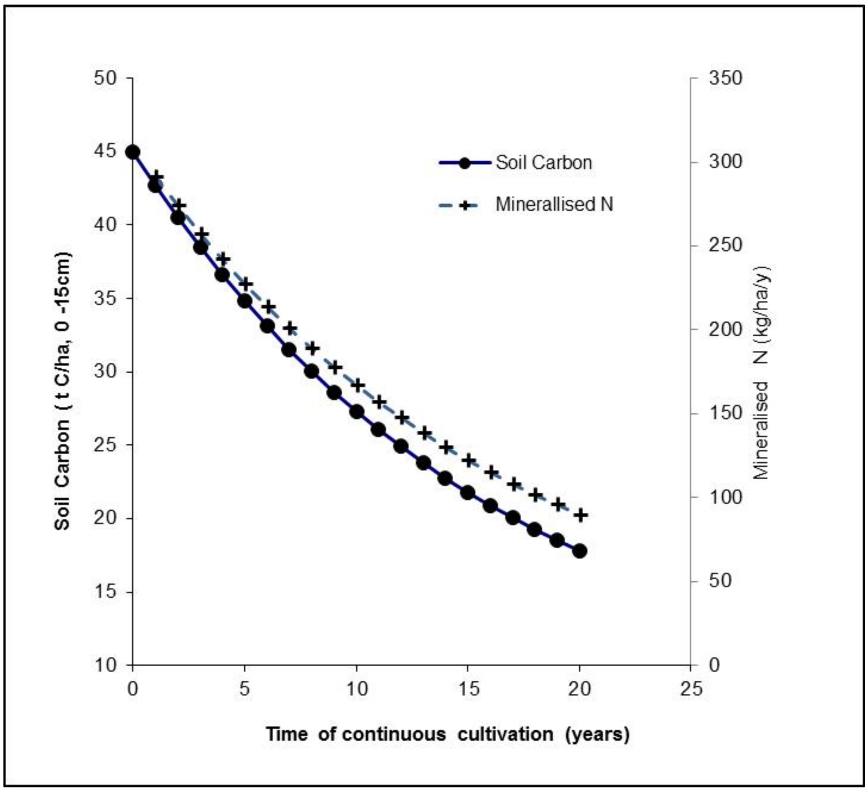


Figure 3.2.1.5 The modelled decline of organic carbon content and amounts of N mineralised annually in the Manawatu silt loam (0-150mm soil depth) under continuous maize cropping.

Nitrogen supply

The rate of N mineralisation was calculated on the basis that the organic matter C:N ratio = 300 : 38 in the pasture soil (Table 3.2.1.1). The rate of oxidation and release of CO_2 and release of plant available NH_4 and NO_3 (mineralised N) from the organic matter each year are dependent upon the amount of decomposable organic matter remaining (Figure 3.2.1.5). The mineralised N can be lost by crop removal, leaching of nitrate, denitrification losses of N_2O or N_2 gases resulting in a gradual decline in total soil N content (Table 3.2.1.1).

The intensity of tillage may also influence N fertiliser requirement by influencing the amount of organic N mineralised. For example, Dowdell and Cannell (1975) found that ploughing caused more N mineralisation and higher soil solution nitrate levels than direct drilling (Figure 3.2.1.6). Fertiliser N requirements under direct drilling are commonly higher but direct drilling may result in lower nitrate leaching losses.

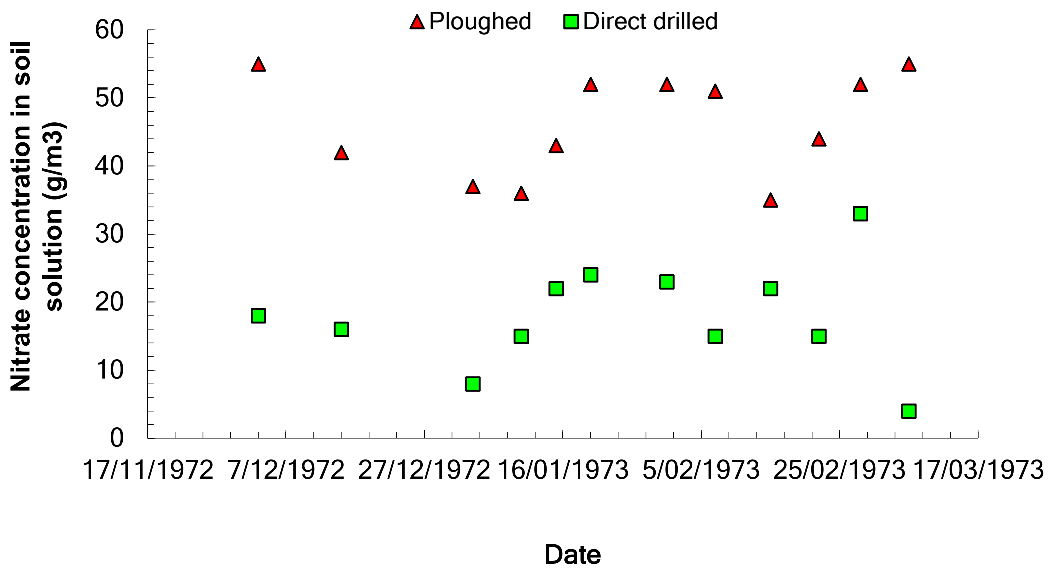


Figure 3.2.1.6 The effect of the intensity of cultivation on soil solution nitrate concentration [Dowdell and Cannell, 1975]

The Manawatu silt loam's ability to provide mineralised N from the organic reserve declines from 550 kg N/ha/y in the first year ploughed out of pasture to approximately 70 kg N/ha/y in year 11 (Figure 3.2.1.5).

Fertiliser N will be required in increasing quantities to maintain maize yields that require approximately 290 kg N per hectare in the standing crop. In simple terms the fertiliser N requirement of the crop can be estimated as follows:

N in standing crop (kg N/ha)/crop N uptake efficiency[1]=amount of mineral N required in root zone (kg/ha)

[[1]Crop N uptake efficiency is the fraction of soil plus fertiliser N used by the crop (commonly 0.5 - 0.8) see later discussion]

Fertiliser N required (kg N/ha) = [amount of mineral N required in root zone + N leached in drainage water - soil N mineralised] (kg/ha)

This estimation of the fertiliser N requirement considerably oversimplifies the complex set of interactions that influence the crops ability to recover both mineralised soil N and fertiliser N during the growing season. Soil temperature, soil moisture, drainage events and form and type of previous crop residues influence both the amount of soil and fertiliser N available for uptake during crop growth and therefore their apparent efficiency of use by the crop. Few definitive experiments have been carried out in New Zealand to measure the separate N uptake efficiencies of soil mineral N and fertiliser N. The research of Haynes (1994) using 15N labelled fertiliser throws some light on the value of these crop N uptake efficiencies for winter wheat grown in the Canterbury region.

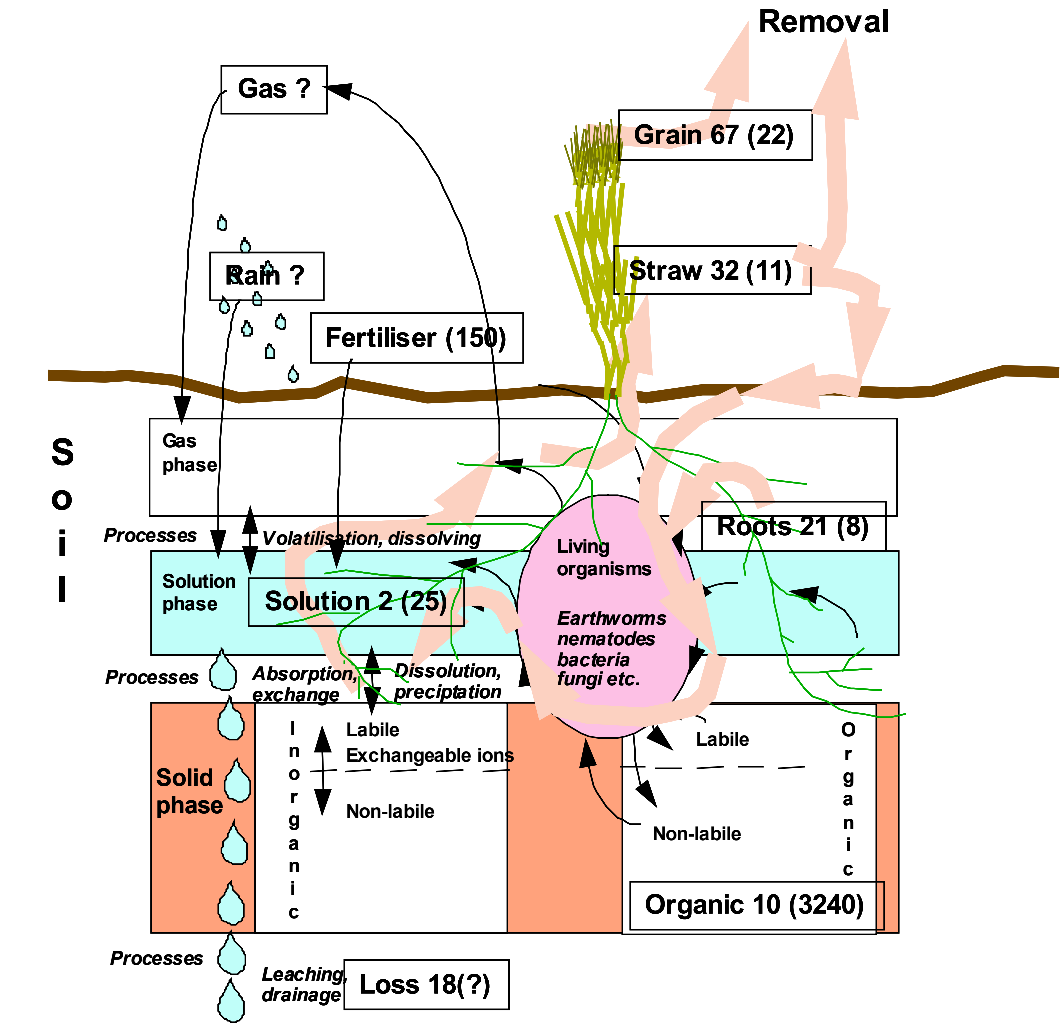


Figure 3.2.1.7 A partial N budget for a 6 tonnes of grain per hectare crop of winter wheat. The numbers in brackets are the amounts of soil-derived N, unbracketed numbers are fertiliser-derived N. The fertiliser N was tagged with the 15N isotope to enable the source of N to be determined (Redrawn from Haynes, 1994)

Figure 3.2.1.7 provides an example of the N budget for a 6 tonne grain/ ha crop of winter wheat grown in Canterbury. The crop requires a total of 161 kg N/ha at maturity, of which 120 kg N was supplied by the fertiliser (early spring side dressing 150 kg N/ha) and only 41 kg N by the soil. In all, Haynes estimates that 66 kg N/ha of the soil organic N pool was net mineralised during crop growth.

The efficiency of soil N use by the crop was 100×41/66 = 62% and the efficiency of fertiliser N use was 100×120/150 = 80%. There are two points to note from these figures. The recovery of fertiliser N by the crop can be more efficient than the recovery of soil N by the crop. This is because the majority of soil N was mineralized immediately after cultivation when the seedling crop was not in a position to take up significant amounts of N before winter leaching. In contrast the 150 kg N fertiliser was side-dressed onto the established crop in early spring when most drainage events were over. The 62% uptake of soil N is however relatively efficient crop use of N compared to the relatively large losses of N by leaching (approximately 500 kg N/ha mineralised, no fertiliser applied, crop uptake of approximately 260 kg N/ha leaving leaching to approximate 240 kg N/ha) that must have occurred in the early years of maize cropping on the Manawatu silt loam (Figure 3.2.1.5). Thus the estimated efficiency of use of soil mineralised N by the maize crop in the first year was 260 kg N in the whole crop/ 500 kg/ha mineralised = 52%. The average drainage volume in the Manawatu could be considered to be 300 mm per winter. Thus, the average drainage water N concentration would have been 80 ppm. Therefore, cultivating pasture soils can lead to losses of nitrate to ground waters in concentrations that far exceed the World Health Organisations suggested drinking water limit of 11 ppm N as NO_3^-.

Careful timing of cultivation and application of fertiliser to avoid periods of excessive drainage are required to achieve high efficiencies of N use and decrease N leaching losses.

A summary of factors which temporally uncouple the arable N cycle

At crop establishment tillage-induced mineralization of soil organic N and basal fertiliser N application raise the soil mineral N pool. At this time newly planted seeds or seedlings do not have developed root systems capable of recovering these relatively large amounts of NH_4 and NO_3 nitrogen. Unpredictable weather patterns may deliver sufficient rainfall to cause either percolation of the nitrate to deeper in the soil profile, or, large rainfall events may cause large amounts of nitrate to be leached completely from the potential crop root zone. That unrecovered nitrate is then on a slow path to ground water. The circumstances described above can be considered to be an uncoupling of the arable N cycle. In the next section we analyse the occurrence of these processes during the establishment and development of an autumn sown crop.

Cultivation, fertiliser application and leaching events

To illustrate the ideas we have covered in this section consider the data for a winter cabbage crop planted in Patumahoe clay loam (Brown granular loam) at Pukekohe on April 1 (see crop management calendar Table 3.2.1.2) into a seed bed prepared from a previous crop of sweetcorn (5.2 tonnes dry matter/ha of crop residues rototilled in).

Table 3.2.1.2   Crop Management calendar

	J	F	M	A	M	J	J	A	S	O	N	D
1. Crop year 1	Sweetcorn											
2. Crop year 2				Cabbage								
3. Cultivation Time (Please indicate cultivation form)	Rototilled residue	↑	Plough									
4. Time of fertiliser application			↑	↑	↑							
5. Amount N applied (kg N/ha)			120	80	80							
6. Harvest and yield fresh weight (tonnes/ha)							40					

To begin with consider the climatic conditions (Figure 3.2.1.8). For the cultivation and incorporation of the sweetcorn stubble and crop residues and 6-week fallow period (15 Feb to April 1) there is a significant soil water deficit (Figure 3.2.1.8 a) and no significant drainage events occur (Figure 3.2.1.8 b). However the soil is sufficiently moist [volumetric water contents between 0.37 and 0.23 resulting from a range of 11 cm water to 7 cm water in the top 30 cm of soil (Figure 3.2.1.9 c)] for mineralization of soil N and decomposition of the sweet corn residues to occur releasing 52 kg N/ha into the soil mineral pool (Figure 3.2.1.9 a). Note that virtually all this increase in mineral N is in the top 30 cm of soil (Figure 3.2.1.9 b). By planting date April 1 the incorporation of fertiliser N (120 kg N/ha) raises the soil mineral N content (0-90 cm) to 268 kg N/ha, 202 kg N/ha of which is in the top 30 cm which by harvest will become the cabbage root zone.

During early plant development (April 1 to May 1), when rainfall brought the soil water deficit to zero on 9-11 April and 22-26 April (Figure 3.2.1.8 a), the soil mineral N pool in the potential root zone (0-30 cm) decreased by 84 kg N/ha (Figure 3.2.1.9 b). Crop uptake accounted for 37 kg N/ha (Figure 3.2.1.9 a), cumulative drainage of 60 mm from events on the 9-11 April and 22-26 April (Figure 3.2.1.8 b)caused NO_3 leaching to the 30 -60 cm and 60 -90 cm depths of 28 kg N/ha and 5 kg N per hectare, respectively (Figure 3.2.1.9 b). Leaching beyond 90 cm soil depth was 18 kg N/ha (Figure 3.2.1.9 a). In 60 mm of cumulative drainage this equates to an average NO_3 –N concentration of 30 ppm. Apparent net mineralization in the whole soil profile was 4 kg N per hectare compared to 52 kg N/ha in the 6 weeks following tillage and residue incorporation. Note how quickly N mineralization slows after the initial 6 weeks fallow.

The next period to focus on is the wet winter period. There was 130 mm of drainage from 30 May to 8 July, which is responsible for the largest amount of nitrate leaching (101 kg N/ha) from the crop root zone (0-30 cm) predominantly derived from the fertiliser side-dressing of 80 kg N/ha applied on 31 May. This large cumulative amount of drainage leaches 73 kg N/ha completely out of the 0-90 cm soil profile. The 73 kg N/ha leached in 130 mm of drainage (1300 metre cubed of drainage/ha) has an average NO_3 –N concentration of 56 ppm.

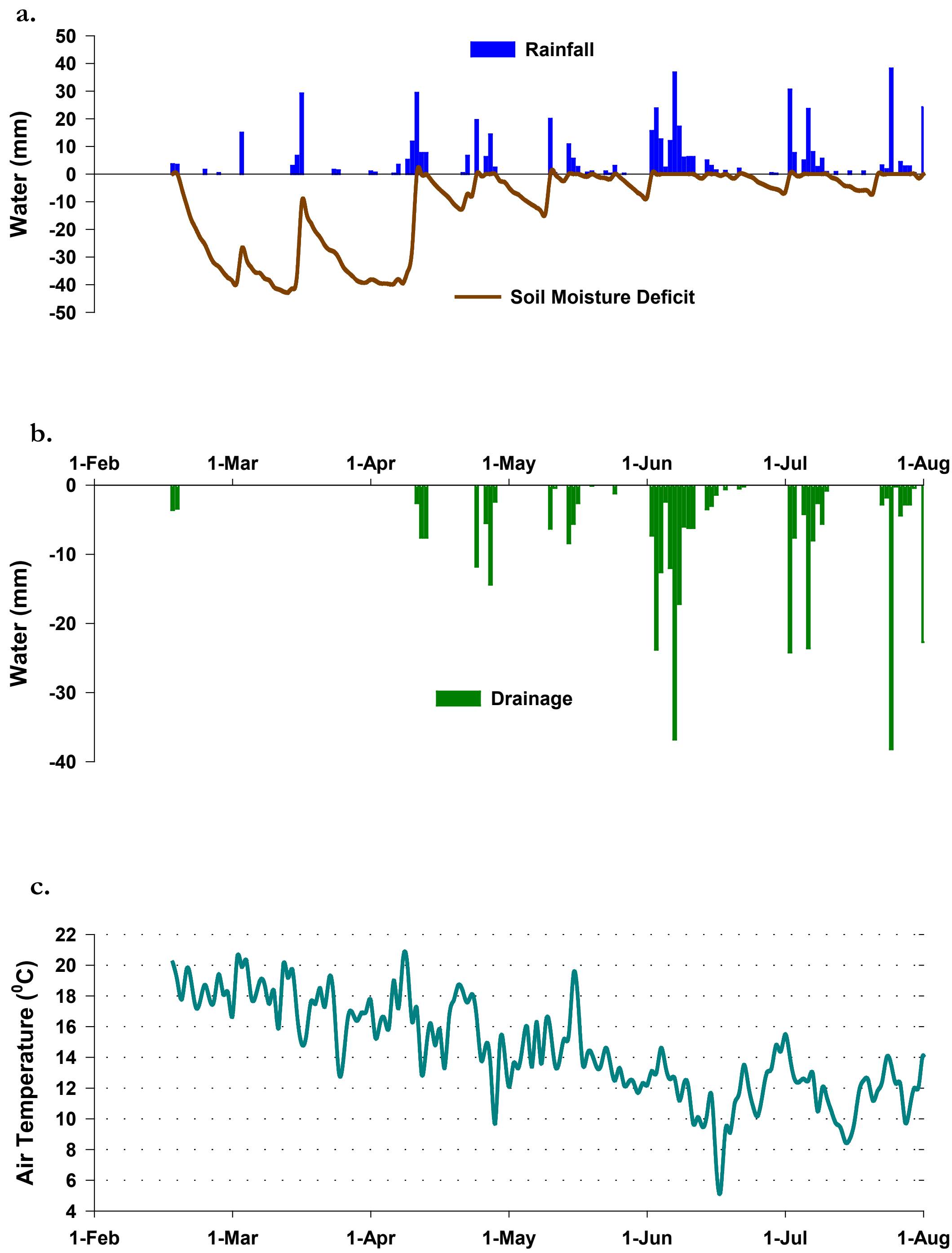
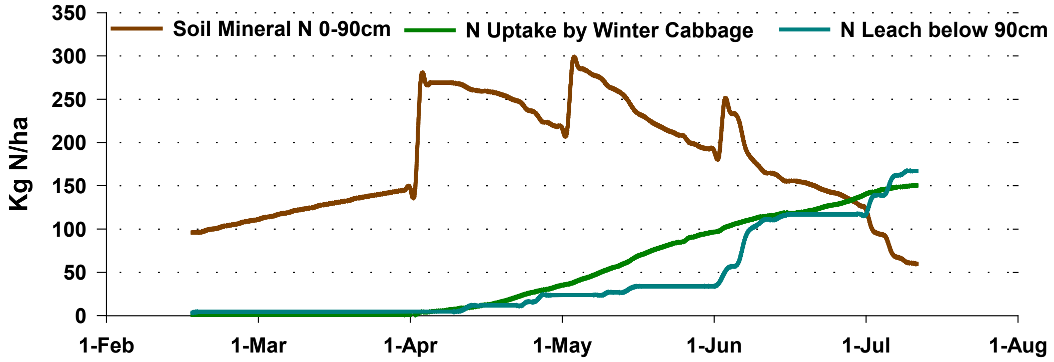


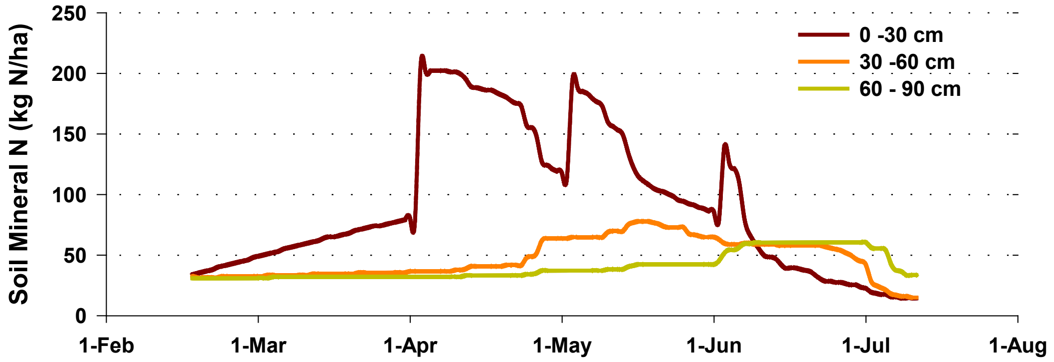
Figure 3.2.1.8 The rainfall, soil water balance and air temperature in Pukekohe for the period of cultivation and winter cabbage growth.

At harvest on 8 July, crop uptake of N is 149 kg N/ha. The apparent crop uptake efficiency of the 280 kg N/ha applied as fertiliser is 53% (149/280x100). The actual crop N uptake efficiency is more like 37% (149/397x100) because the total net mineralised N (117 kg N/ha) plus the fertiliser (280 kg N/ha) N pool was approximately 397 kg N/ha.

a.



b.



c.

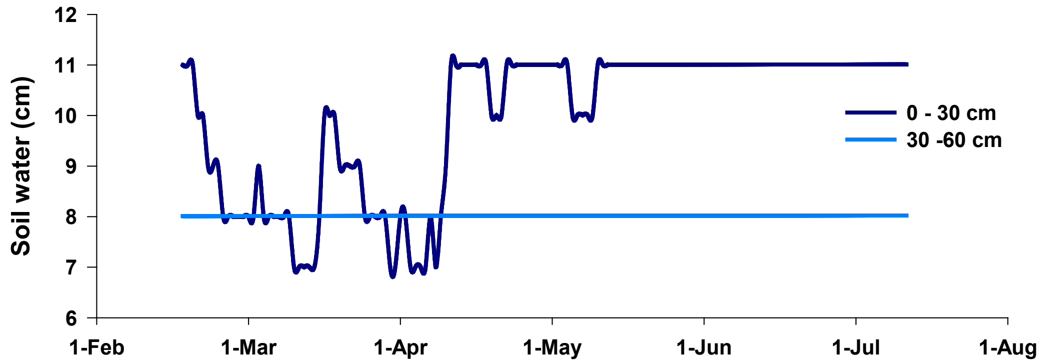


Figure 3.2.1.9 The variation in soil mineral N in 0-90 cm soil profile, crop N uptake and N leached below 90 cm and the soil water content (0-60 cm) in Pukekohe for the period of cultivation and winter cabbage growth (planting date April 1).

Summary

In summary, cultivation for cropping accelerates soil organic matter decomposition and leads to high soil NO_3^- concentrations early in the growing season before the plant N demand is high. If soil water deficits are low, drainage results as a consequence of rain and leads to nitrate leaching and inefficient use of soil and fertiliser N.

Decreased fallow periods and split applications of N fertiliser just prior to periods of greatest crop N demand and controlled released fertilisers can be used to increase plant use of fertiliser N.

Revision self-test

In this introduction to the arable N cycle we have tried to emphasise how dynamic the plant availability of soil N is and how soil management, season and crop management will influence the fate of potentially plant available N. To complete this section consider Figure 3.2.1.11 that shows the profile of mineral N with depth for the winter cabbage crop described in Figures 3.2.1.9 and 3.2.1.10 and answer the following questions:

1) Explain the increase of soil mineral N in the top 20 cm on March 31st.

2) Explain the increase of soil mineral N in the top 20 cm on April 1st.

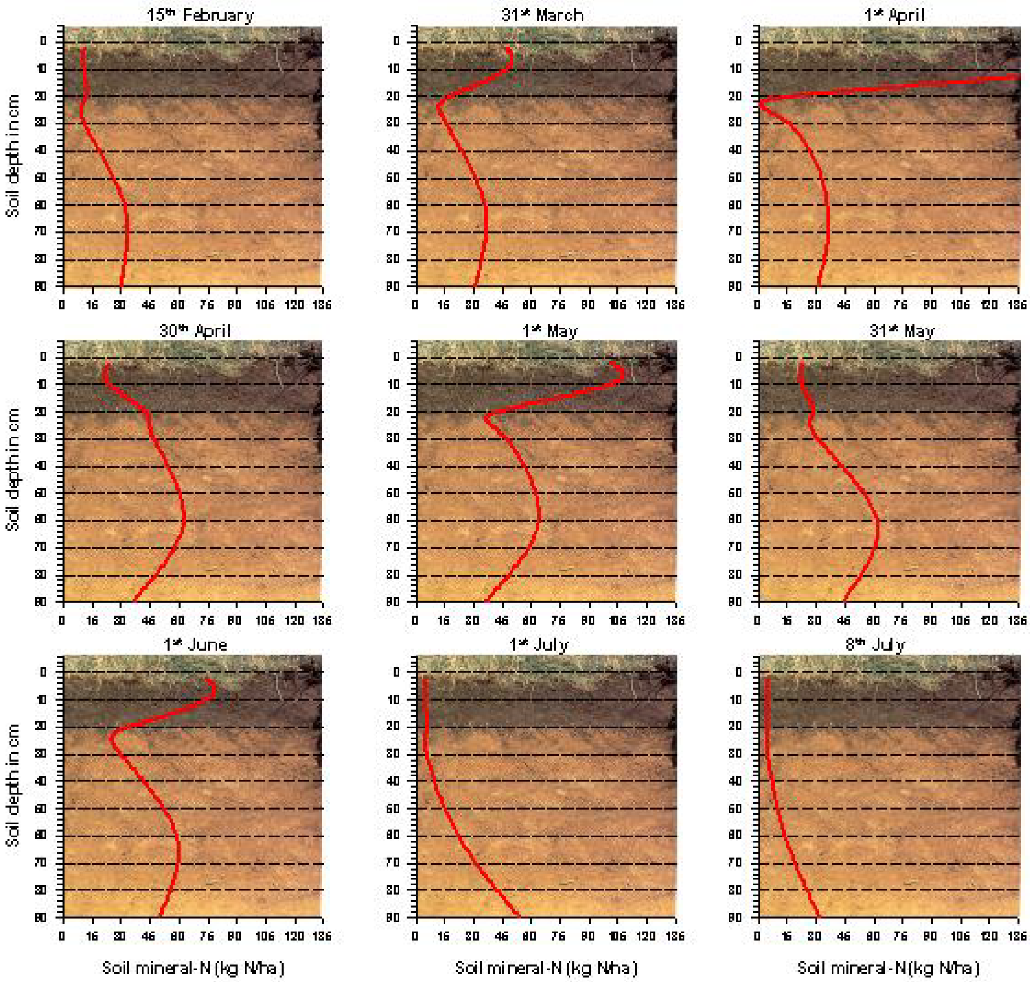


Figure 3.2.1.10 Distribution of soil mineral-N for the Patumahoe clay loam soil profile throughout a winter cabbage season.

3) What was the major reason for N decrease in the top 20 cm on April 30th and what was the main source of increase N at 60 cm? What was the minor source?

4) Winter cabbage was harvested July 8th and 50% of the above ground crop was removed with the outer leaves and stems left behind on the soil surface. If the soil is left fallow until summer, draw two soil profiles showing the soil mineral-N concentration one and two months after harvest. Quantify and explain the differences between the two profiles (Use climate data in Figure 3.2.3.1).

5) Total drainage volume from cultivation to harvest was 300 mm. If the average soil volumetric content at field capacity (0-30 cm) is 0.37 how deep will the drainage front be at the end of winter?

6) The total N fertiliser application for winter cabbage was 280 kg N/ha split in three applications (1 at planting and 2 side-dressings). Explain what will happen to the fertiliser recovery efficiency if all the fertiliser was incorporated in the seedbed.

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3.2.2 Predicting fertiliser nitrogen requirements of arable crops

Key Learning Objectives

After studying this section you should be able to:

1. Describe and compare the effectiveness of the various methods for determining N fertiliser requirements of arable crops.
2. Describe the applications and limitations of the use of plant analysis in determining N fertiliser requirements for arable crops.

Introduction

Extensive research has been conducted in predicting the N fertiliser requirements of crops, but in many instances only limited success has been achieved because of the complex nature of the behaviour of N in the soil (see N cycle Figure 3.2.1.1). Fertiliser N recommendations for crops generated in the 1970's were based on the amounts of residual N in soils from previous cropping and today they can be considered as static models. The reason for this is that fertiliser N requirement depends not only on the supply of N from mineral and organic sources in the soil, but also on the growth of the crop, all of which are affected by climatic conditions during the growing season and soil and crop management practices. With the increased use of fertilisers, scientists, consultants and farmers started to realise the potential environmental problems that use of fertiliser, along with an increase in pasture and crop production, were causing to the environment. It was at this stage that the concept of N leaching started to play a role in fertiliser recommendations and seasonal models considering the N status of the crop and the soil during the crop growth period were developed. However in the last decade, the development of advice on use of N fertilisers for vegetable crops in NZ has become difficult because of the numerous crops and management practices used by the farmers. The developments of dynamic models that consider soil and plant interactions are now becoming popular to provide solutions. Dynamic models are based on mathematical equations describing processes that govern climate, soil and plant nutrition. Easy to use computer software have been developed to run these models. However, not all dynamic models can simulate a wide range of soil-plant-climate scenarios because of the complex uncertainty of many soil/plant processes cannot be appropriately modelled.

This section briefly describes the history of N fertiliser recommendation in NZ. It starts with the earliest theories on previous cropping or paddock history (static models), incorporating later concepts on residual soil mineral N and N status of the crop (seasonal models) and nowadays using computer models incorporating more sophisticated equations describing the processes in the soil and plant system and their interactions with the climate (dynamic models).

Previous cropping or paddock history: a static model

Stephen (1980, 1982) reviewed earlier field trials on wheat in New Zealand which showed that yield responses were dependent on paddock history related to the previous crop. In one trial, spring application of N only increased wheat grain yield in the second and third winter sown wheat crops, but not in the first after pasture. In this example, the reason for wheat not having a fertiliser N response in the first year is that much of the N taken up by the crop was supplied by the soil rather than by the fertiliser. The N supplied by the soil originated in the soil organic matter and decaying residues of the previous pasture crop. The quantity of decomposable soil organic matter, its N richness and the quantity and N-richness of the previous crop residues are major factors that determine how decomposition (mineralisation) of the organic materials influences N availability for the next crop. Characterization of the N-richness of organic materials is best achieved by use of carbon to nitrogen (C:N) ratios or by percentage N content of organic materials. For example, wheat responded to applied N fertilisers most frequently when the preceding crop was cereal and least frequently when it was a pasture or a forage crop.

N Index system

Recommendations for N fertilisers for arable crops in the 1980's, in NZ and the UK were made using a simple N balance model where:

Fertiliser N required = Crop N demand – Soil N supply (Eq.2)

The soil N supply was estimated using a paddock history approach. These recommendations involve the practice of calculating credits for N supplied by legumes or animal manures and debits based on cultivation history and crop removal.

Soil N Supply

The NZ MAF Soil Fertility Service estimated the soil N supply using a N index on a 0 to 10 scale (Table 3.2.2.1) with 10 being a high soil N status, achieved after many years in clover based pasture, and 0 being a very depleted soil following continuous cropping with no restorative crops (Metherell *et al.*, 1989). One unit on the N index scale equates to an N supply of 100 kg N/ha.

The soil N index system provides a simple combined estimate of the amount of soil mineral N present at planting plus the amount of N that will mineralise from soil organic matter and the previous crop residue during crop growth. As can be seen from the high scores given to clover based pastures and low scores given to cultivated soils the amount of N mineralised from soil organic matter and previous crop residues is the main factor changing the index.

Starting from the base index (normally 10 for good permanent pasture) subsequent depletive crops (e.g. cereals) reduce the index, while restorative crops (e.g. grazed forage legumes or periods of clover based pasture) will increase the index. Heavy applications of fertiliser will reduce the effect of depletive crops while in situations conducive to winter leaching extra index points are deducted. However, the limits of the 0 to 10 scale cannot be exceeded.

Crop N Demand

The crop N demand is the total quantity of N that must be absorbed by the crop from soil and fertiliser sources to permit the potential maximum growth. It depends on a predicted yield, a harvest index (% crop N harvested), and the critical %N of the harvested component, defined as the minimum %N needed for maximum growth. The rationality behind the concept is that the target yields and in the case of cereals, the target protein content are important determinants of the crop demand (see Table 3.2.2.1).

Recommendations based on paddock history are highly empirical and subjective. It does not consider the climatic effects on soil N supply during the growth of the crop, including the effects of temperature on N mineralisation, and rainfall on N leaching. Also the total crop N demand increases with increased yield and predicted target yield errors arise in not being able to predict the target yield accurately.

Table 3.2.2.1 MAF Soil Fertility Service N Index (an index of soil N supply to crops) for paddocks with different cropping histories and management (Metherell et al., 1989)

Paddock history	**Nitrogen index**
Clover based pasture (5 or more years old)	10
Lucerne (5 or more years old)	7-10
Poor pasture where clover growth and N fixation have been restricted by a lack of fertiliser or lime	7
Very poor pasture with very little clover	5
5 or more years mixed cropping (including restorative crops)	3
5 or more years continuous cereal cropping	0
New crop effects (per year)	
Depletive	
Cereals (less than 5 t/ha)	-2
Cereals (greater than 5 t/ha)	-3
Maize – grain or forage removed*	-3
Vegetables*	-3
Potatoes*	-3
Forage crops (non-leguminous) removed	-3
Oilseed rape	-2
Grass seed (no clover)	-1
Brassicas (grazed in situ)	-1
Cereal greenfeed (grazed in situ)	-1
*average yield. Deduct one extra point for high yielding crops	
No net effect	
Grain legumes (peas, beans, lupins)	0
Forage legume (peas, beans, lupins) – removed	0
Grass seed or hay (followed by good clover growth)	0
Restorative	
Processed green legume (peas, beans –nodulated, with residue Grazed or ploughed in)	+1
Forage legume grazed in situ	
– low to medium yield	+1
– high yield	+2
Clover seed crop	+3
Grazed pasture (good clover vigour)	+2/annum
Poor pasture	+1/annum
Lucerne (hay)	+1/annum
Lucerne (grazed)	+2/annum
Previous N fertiliser	
Consider N applied in previous 2 years	
Heavy N fertiliser applications reduce the effect of depletive crops (i.e. tend to increase the index)	
+1 point per 100 kg N	
Winter nitrate leaching	
In situations conducive to winter N leaching index points are deducted. All of the following conditions must be met:	
N index must be 5 or greater	
Paddock must be fallowed or in autumn sown crop	
Soil moisture status at field capacity or greater	
Heavy rainfalls induce leaching	
With up to 50 mm rainfall in one storm deduct one index point. When rainfall has been of greater intensity, deduct two points.	

Seasonally adjusted N requirements

Key inadequacies of the index model were that no adjustments could be made for seasons that differed markedly in climatic conditions. For example, a cool wet period prior to planting may result in low organic N mineralisation and leaching of nitrate from the fallow soil. Thus soil N supply may be overestimated and fertiliser N undersupplied. This section describes the concept of soil mineral N and tissue testing as the typical input parameters for seasonal models. A major advantage of seasonal models over static models is the ability to customize the N fertiliser requirements for the growing season in question.

Pre-plant soil mineral N

During the 1970's in some overseas countries and in NZ, prediction of N fertiliser requirement of crops was based on measuring the amount of soil nitrate or mineral N ($NO_3^- + NH_4^+$) in soils before active plant growth commences. The method was employed successfully in Germany to recommend the rate of N fertilisers required for winter wheat (Becker and Aufhammer, 1982). It involves the determination of mineral N concentration in the soil within the root zone (0-900 mm depth) before spring growth begins.

In Canterbury, Ludecke (1974) demonstrated a significant relationship between soil nitrate-N levels in the 0-900 mm soil depth during the late-winter/early-spring period and grain yield response of autumn-sown wheat to N fertiliser. This relationship was the basis for the 'deep nitrate' test used to recommend N fertilisers during the 1970's (Stephen, 1980). The test assumes that no fertiliser N is required when the soil N level (Ns) in the 0-600 mm depth in August/September exceeds 12 mg N kg^{-1} soil ($Ns_{(0\text{-}600)} \cong 70 - 90$ kg N/ha). Below this level, N requirement of autumn-sown wheat increases linearly with the decrease in nitrate-N up to a maximum requirement of 85 kg N ha^{-1}.

Although the 'deep nitrate' method has some advantages over the 'previous cropping history' approach, it also failed to accurately determine the N fertiliser requirements of crops in many instances. Possible reasons for the failures are: nitrate levels in the soil are affected by heavy rain before and after sampling in the late-winter/early-spring period because of leaching losses, therefore, nitrate concentration varies with time of sampling; also the amount of mineral N released in the soil during the growing season is not incorporated in the test.

Pre-plant soil mineral N plus mineralisable soil N

A considerable portion of the N taken up by crops can be derived from the N released from the mineralisation of soil organic N reserves and, therefore, this factor should be included in any method of predicting the N fertiliser requirement of crops. For example, in the field trial conducted at Oamaru by Williams and Tregurtha (2003) the Broccoli crop must have derived at least 102 kg N ha^{-1} via mineralisation of soil N when soil mineral N in the 0-600 mm soil depth at planting was 39 mg N ha^{-1} and fertiliser addition was 59 kg N ha^{-1} (see study guide section 3.2.3 Table 3.2.3.1).

Based on trials carried out on wheat in Canterbury, Quin *et al.* (1982) reported that yield of wheat without fertiliser was related to a combination of the initial mineral N at sampling (Ns) and an increase in mineral N ($N_{M(L)}$) on aerobic incubation for 7 days at 37ºC.

Expected yield in the absence of N fertiliser (t ha^{-1}), Y_0 is given by:

$$Y_0 = 1.0 + 0.0417\,(Ns + 2\,N_{M(L)}) \qquad \text{(Eq.3)}$$

Mineral N and mineralised N measured in fresh moist soil samples from the 0-150 mm depth were used for this relationship. Data from this depth correlated best with yield as compared to samples from greater (0-600 mm) depths (as in 'deep nitrate test').

An additional component in this recommendation was that the amount of N fertiliser required to maximize yield was calculated by subtracting Y_0 from the potential yield Y_P and multiplying the difference by 40 (Canterbury) or 50 (Otago-Southland).

$$\text{N to apply (kg ha}^{-1}) = (Y_P - Y_0) \times 40 \qquad \text{(Eq.4)}$$

The value of 40 equates to a 1 tonne grain yield response per 40 kg N, a value well established in previous trials in Canterbury.

In Canterbury, N responses of wheat have been shown to be highly dependent on the availability of soil moisture. The method of Quin *et al.* (1982) was established on soils without moisture stress. Therefore, it should not be used indiscriminately on non-irrigated wheat (Goh, 1983).

Stanford (1973) proposed the following simple model to determine the N fertiliser requirement of crops.

$$N_C = e_i N_i + e_m N_m + e_f N_f \qquad \text{(Eq.5)}$$

where:

N_C is crop N uptake

N_i is the measured initial quantity of mineral N in the soil profile

N_m is the estimated N mineralized during the crop season

N_f is the amount of N fertiliser needed

e is the efficiency of crop recovery from each of the N sources

Therefore, the fertiliser N requirement, $N_f = (N_C - e_i N_i - e_m N_m) / e_f$

N_i can be measured in the laboratory on samples taken in the field at planting. N_m needs to be estimated by the measurement of soil conditions in the field together with the use of long-term weather forecasts.

The efficiencies of crop N recovery (e_i, e_m and e_f) from the various N sources vary from 0.5 to 0.8. Climate (e.g. rainfall), soil properties (e.g. texture), and farm management (e.g. rate, frequency, timing and placement of fertilisers; crop residue incorporation) all influence the crop N recovery. N recovery efficiencies have been measured using 15N tracer techniques. Studies have shown that crop recovery of N in legumes applied to soils is lower than that of N applied in fertilisers and N recovery from side dressed N fertiliser is generally higher (0.65-0.8) than that from N applied to the seed bed (0.5-0.7). N recovery decreases with increase in rate of fertiliser application and increases with increase in plant growth because of increased root growth. Leaching of N below the root zone reduces the N uptake efficiency of crops.

The limitations of models similar to that of Stanford (1973) are that the efficiency factors may vary markedly with seasonal changes in climate, drainage and choice of timing and application rate of fertiliser.

Plant analysis - tissue testing

The objective of tissue testing for N is to determine whether the crop has sufficient N for its growth. If insufficient N is detected in the early stages of plant growth N side-dressing requirements can be modified to provide extra fertiliser N. Nitrogen sufficiency is described in terms of being inadequate, optimal, or excessive. Concentration of N in plant tissues can provide a numerical index of sufficiency only if the tissue test has been calibrated through research trials. Chemical analysis of plant parts for N (e.g. sap tests for nitrate) is not generally used for predicting N requirements because of the complexity or lack of reliable quantitative relationships between plant nitrate content and crop yield. However, plant analysis can be used successfully to complement soil tests or model predictions, especially for monitoring the adequacy of N in the plant at sensitive growth stages or for providing information on the amount of N fertiliser to be applied to subsequent crops (Goh, 1983).

In California, Hartz (1997) reported that the majority of vegetable growers use tissue testing to determine nutrient status of the crop. The midseason sampling of petioles for celery and broccoli or leaf midribs for cauliflower and lettuce is the most common growth stage and plant part for NO_3-N determination. Hartz's (1997) research shows that nitrate-N tests were found to discriminate vegetable farms having sufficient N supply from those having marginal or deficient N supply, but they were found to be reasonably insensitive measures of soil N supply in farms of moderate to high nitrate-N availability. In this case, the tissue tests commonly used to evaluate N status have little ability to detect excessive applications of N. However, in crops such as corn this might not be the case. The "end-of -season cornstalk test" is a tissue test developed in the USA to evaluate N management practices. The cornstalk tissue test measures levels of N excesses as well as N deficiencies (Binford et. al. 1992).

Tissue testing provides a site-specific assessment of N sufficiency that cannot be attained easily by testing soils or measuring yields. If in the future new research and technologies move towards site-specific N needs of crops, then tissue testing will be an essential tool for evaluating and improving these new technologies. Research done in the US has demonstrated that remote sensing can be used to measure plant characteristics that indicate N sufficiency.

Research indicates a close link between leaf chlorophyll content and leaf N content, and the reason is that the majority of leaf N is contained in chlorophyll molecules. The chlorophyll meter (spectral sensor) enables users to quickly and easily measure leaf greenness, which is affected by leaf chlorophyll content. A number of factors, one being N status of the plant, affect chlorophyll content or leaf greenness. Since the chlorophyll meter has the potential to detect N deficiencies, it also shows promise as a tool for improving N management. The chlorophyll meter has several advantages over other tissue testing methods. A reading that indicates adequate N is not affected by luxury consumption; a plant will only produce as much chlorophyll as it needs regardless of how much N is in the plant (Peterson *et al.*, 1993). It is not necessary to send samples to a laboratory for analysis, saving time and money. Producers can sample as often as they choose, and can easily repeat the procedure if they question the results. Using a chlorophyll meter to monitor leaf greenness throughout the growing season can signal the approach of a potential N deficiency early enough to correct it without reducing yields. Using a chlorophyll meter as an N management tool is especially appropriate where additional N can be applied through the irrigation system (Peterson *et al.*, 1993).

Soil, crop, climate, season sensitive N requirements: dynamic models

In the past, the focus of N fertiliser recommendations has been concerned with crop production and profitability. The methods of determining the N fertiliser needs of crops discussed so far were based on empirical interpretations of laboratory and field trial results and farmers experiences. Quantification of such systems was achieved using empirical regression models that had limited applicability due to their site-specific nature. They do not always give correct information when the methods are extended to a wider range of soil, plant, and climatic conditions than used in the initial establishment of the methods. Therefore, a more robust approach to predicting the N requirement of crops is needed. This should attempt to measure quantitatively the interactive processes of soil, crop and climate affecting crop responses to N and integrate them into a practical model for general use. These models have the ability to incorporate different systems of soil and crop management that could impact greatly on soil N supply or efficiency of use of soil and fertiliser N. The use of knowledge-based crop growth models to predict crop production, and water and nutrient dynamics in the soil and plant, has become common place as we become more able to quantify those processes and as the availability of powerful computers needed to run those models become more readily available.

Simulation models (considering crop growth, soil management, or both) have been built in UK (e.g. N-ABLE), U.S.A (e.g. CERES) and New Zealand (e.g. Potato Calculator, Wheat Calculator) to offer decision support for determining the rates of fertiliser N required by vegetable and cereal crops. The more sophisticated models account, in a mechanistic way, for soil processes that govern soil and crop residue N supply to the growing crop. They allow fertiliser N rate and timing to be selected to have the best chance of improving N efficiency. A dynamic model to study the N-dynamics in vegetable cropping is described below. The model is called N-ABLE and was developed in the UK by the Horticulture Research International. This course uses the N-ABLE model to demonstrate how dynamic models function and how they can be used to illustrate the important factors influencing the efficient use of N by crops.

N-ABLE – Crop N requirement model

The development of fertiliser N recommendations for vegetable crops in the UK has been made difficult by the numerous crops and different management practices in which they are grown (Greenwood *et al.* 1996). For example, the nature of crop residues and whether or not they are incorporated in the soil can greatly influence N requirement to subsequent crops. In addition, concern about nitrate pollution from arable soils required the need for more efficient ways of using fertilisers. This led Greenwood *et al.* (1996) to develop an easy-to-use N simulation model called N-ABLE to improve fertiliser practices when crop residues are incorporated into the soil instead of removed. N-ABLE is a deterministic dynamic N simulation model design to simulate the growth of 24 vegetable and arable crops.

Figure 3.2.2.1 shows a diagram of the relationships between the more important variables in the N-ABLE model. The diagram shows the different components of the weather (daily rainfall, mean air temperature, and potential evapotranspiration) represented by a single box on the right hand side of the diagram and the various soil properties by a single box on the left hand side (Greenwood 2001). The variables concerning the soil are given in the upper part of the diagram and those concerning plants in the lower part. The numerous processes in the model are represented by equations. These are solved for each day of the simulation and the variables updated accordingly. The main inputs to the equations used for calculating each variable are given by the sources of the arrows in the diagram. For example, the %N in the plant is calculated from the total N in the plant and the plant dry weight (D.J. Greenwood 2004).

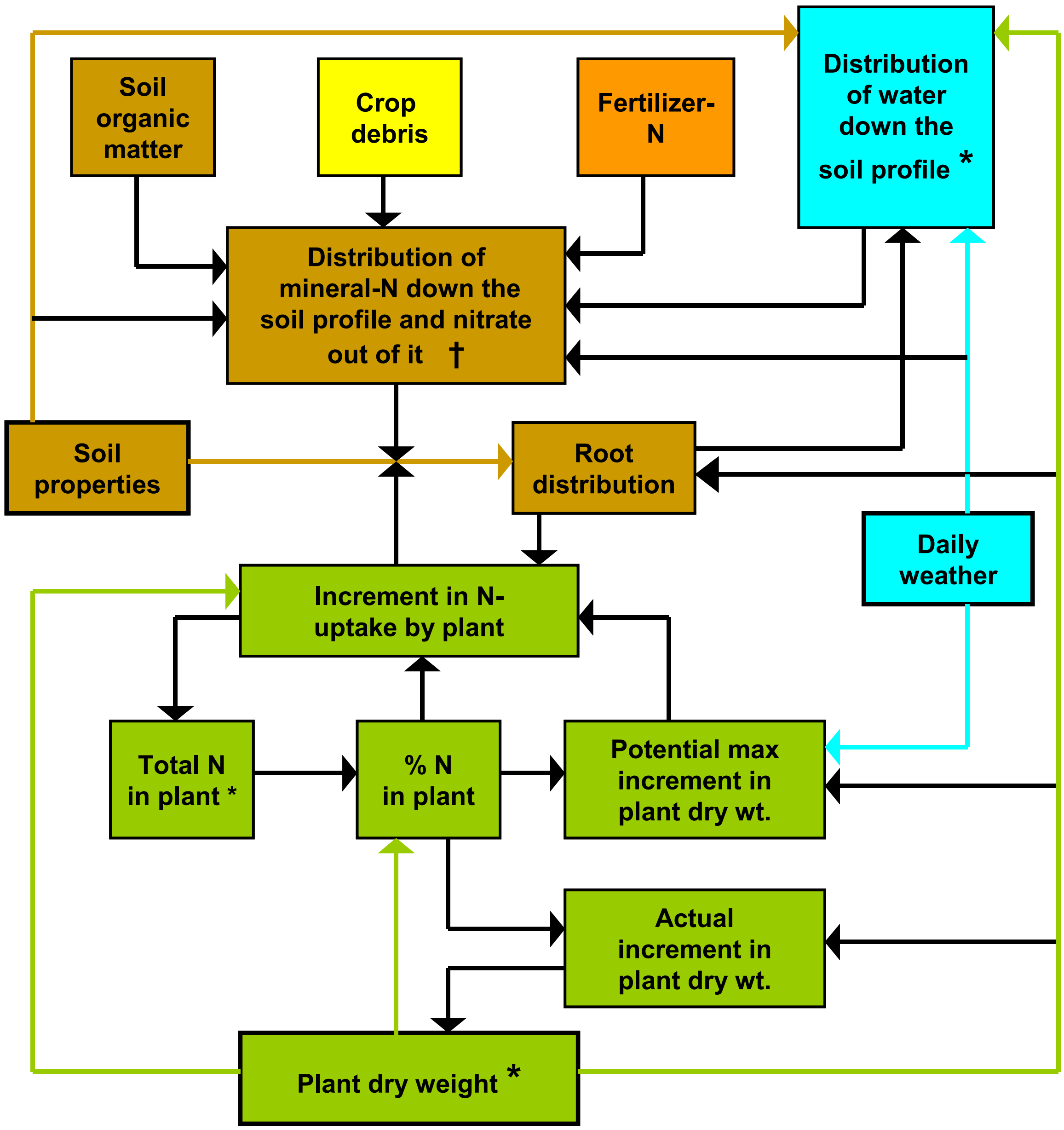

Figure 3.2.2.1 Flow diagram of N-ABLE (Redrawn from Greenwood, 2001)

The meanings of the symbols as described by Greenwood (2001) are as follows:

1. **Boxes:** variable quantities or in some cases, such as 'Soil properties', groups of quantities.
2. **Arrows:** the interdependence of the variables.
3. **Asterisks:** variables the initial values of which are essential for running the model.
4. **Dagger:** Mineral-N is (ammonium + nitrate) N

A typical simulation run proceeds in 3 phases as described by Greenwood (2004):

1. **Pre-planting phase:** in this phase only variables in the upper part of the diagram change. The model re-calculates for each day the decomposition of crop debris, the decomposition of soil organic matter, and the distribution of soil water. It also, re-calculates their effects together with those of the daily weather, various soil properties and the effects of any application of fertiliser, on the distribution and leaching of mineral-N down the soil profile.
2. **Crop growth phase:** in addition to the above, the model re-calculates, for each day, values of the variables in the lower part of the diagram. These are potential maximum increment in dry weight, root distribution, increment in N-uptake by the plant, total N in the plant, %N in the plant, actual increment in dry weight, and plant dry weight.
3. **Post harvest phase:** the operations for each simulation day are the same as in the pre-planting phase.

Theory and description of N-ABLE

Soil parameters

In the model the soil is visualized as consisting of 20 consecutive 5 cm thick layers. The roots penetrate the layers (laterally and vertically in the soil) and extract nitrate and water from them to a depth that increases as the plant grows or until they reach a hard pan or other barrier, which prevents further root penetration.

Fertiliser and crop debris are incorporated in the uppermost layer of soil. Microbial breakdown of the resident endogenous soil organic matter always increases soil mineral-N. But mineral-N can be either produced or immobilized during the decomposition of crop debris, depending on its C/N ratio (N-richness). When mineral-N is released it is converted to ammonium-N, which is then nitrified to nitrate-N. Mineralisation is assumed to convert organic-N directly to nitrate without any accumulation of ammonium ions. The model assumes that nitrate-N is not adsorbed on the soil. It can then be taken up by plant roots, can be leached downwards during rain or can move upwards during evaporation from the soil surface (Greenwood *et al.* 1996).

In summary, for each day during the simulation the following calculations are made for each soil layer:

- the mineralisation of soil organic matter,
- the mineralisation and immobilisation of N as a result of microbial metabolism of freshly incorporated crop debris,
- the upward and downward movement of water and nitrate, and
- the amount of nitrate in each layer.

For example, consider the soil N profile generated by N-ABLE in Figure 3.2.2.2. Crop residues with a 37 C:N ratio were incorporated in the soil the 15th of February and a winter cabbage crop was planted 1st of April and harvested 8th of July. Crop debris incorporation, its decomposition and endogenous (resident) soil organic matter decomposition raise the soil N concentration in the 0-15 cm depth during the month of February and March. Note during these months Figure 3.2.2.3 shows there were no significant drainage events. However, in April, May, and June the climate data shows 27 drainage events and a total of 248 mm of cumulative drainage. These drainage events are responsible for soil N concentrations increasing in the 20 to 90 soil depths. During these months soil temperature also decreases and mineralisation slows down. From 1st April onwards the crop established and begins to take up N from the upper soil layers. Soil N in the 0-10 cm and 10-20 cm layers show a decrease as the net sum of crop N uptake and nitrate leaching became greater than the rate of nitrate generation from soil organic matter mineralisation (Figure 3.2.2.4).

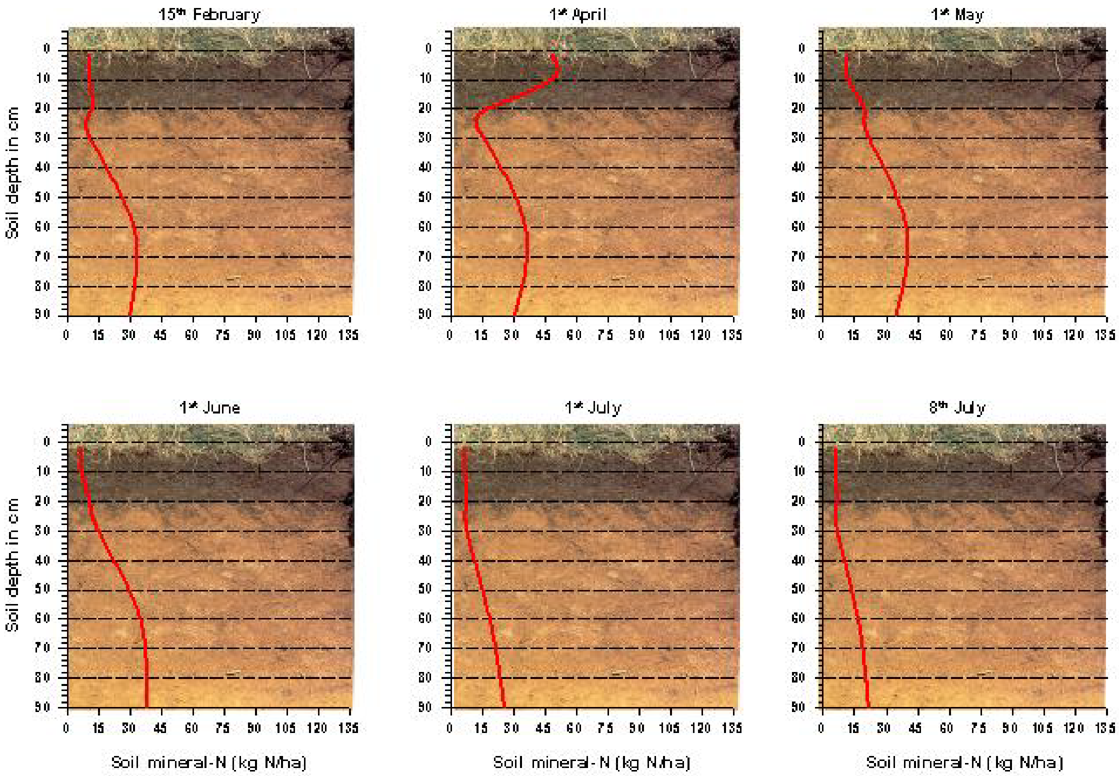

Figure 3.2.2.2 Distribution of soil mineral-N for the Patumahoe clay loam soil profile throughout a winter cabbage season.

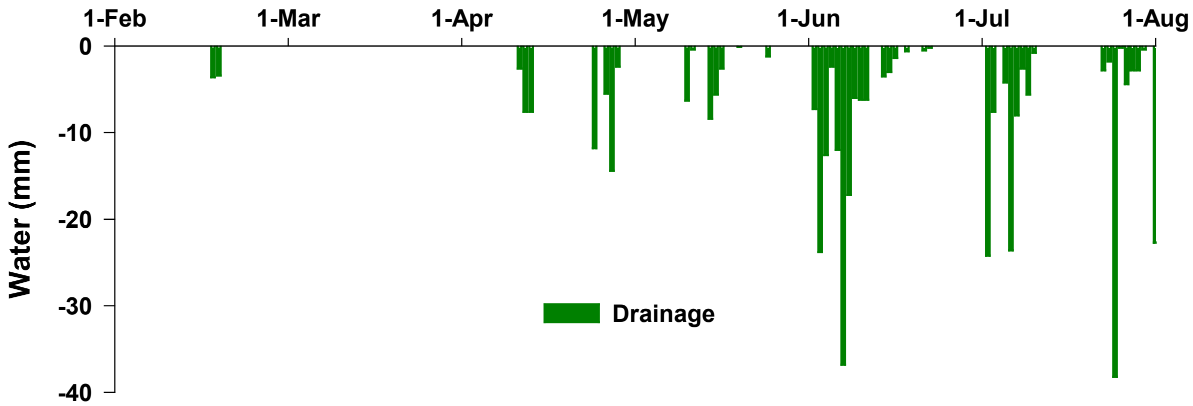

Figure 3.2.2.3 Drainage events for Patumahoe clay loam soil

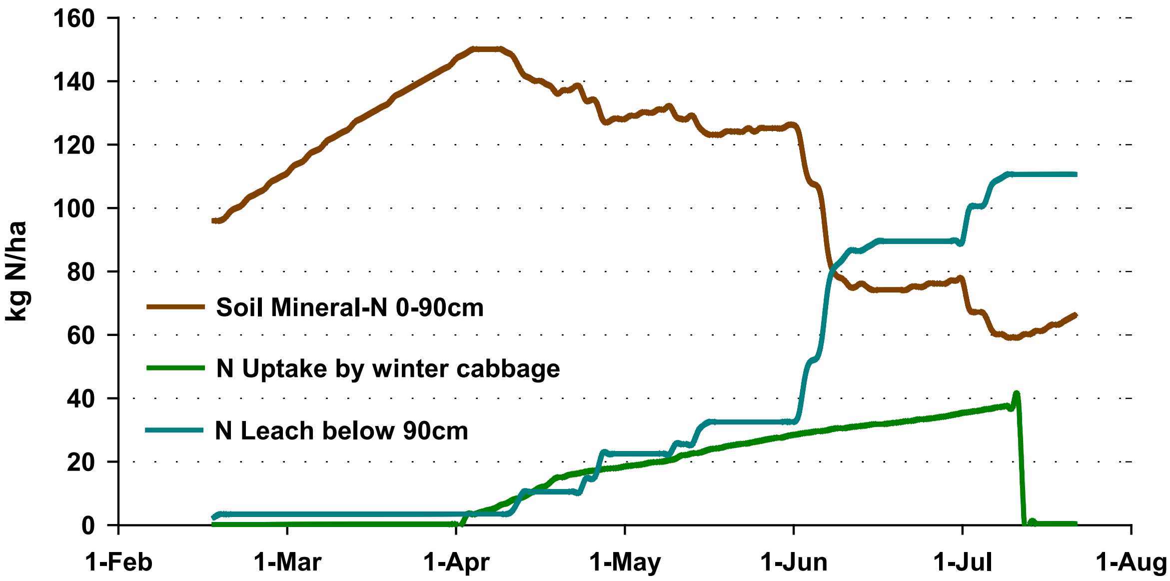

Figure 3.2.2.4 Simulated soil mineral-N, N leach below 90 cm, and N uptake by winter cabbage

Crop parameters

The estimation of crop growth is based on the proportion of incoming radiation that is intercepted by the leaves. In the vegetative stage, interception and thus growth of dry matter increases roughly in proportion to plant dry weight. As the plant gets bigger, the leaves overlap and the proportion of radiation intercepted per unit of plant weight declines. The amount of N in the plant can limit crop growth and consequently limit the potential yield. Most plant N can be found in the photosynthetic components (leaves) and comparatively small amounts are in the structural and storage tissues of plants. In small plants, the photosynthetic components constitute a large proportion of the total plant weight, and thus the %N in the plant is large. As the plant grows the structural and storage tissues constitute an increasing proportion of the total dry weight so that the %N of the entire plant declines (Figure 3.2.2.5). In summary, plant growth is calculated using the daily mean air temperatures, the plant mass per unit area, and plant N concentration relative to the critical concentration for a plant of the same weight. Critical %N is defined as the minimum %N needed to permit maximum growth. In the model, crucial to the estimation of crop growth are 2 crop-N parameters. These are the critical N concentration and the maximum possible N concentration, and a relationship describing how they decline with increasing plant growth.

To calculate crop uptake, first the model calculates the potential maximum crop demand for N for each day from plant weight and N concentration, the maximum plant weight that could be attained by the end of the day and the critical %N of a plant of that size. Then N-uptake is calculated from the potential maximum crop demand and the amount of mineral N within the rooting zone after adjusting for immobilisation, denitrification, etc. A new %N of the dry matter in the plant is calculated, which together with the plant weight and the temperature are used to calculate the increment in plant weight. Each of these calculations is repeated for every day during the growing period (Greenwood *et al.*, 1996).

In summary, the following calculations are repeated for each day during the growing period:

- The potential maximum dry weight
- The potential maximum N uptake
- The actual N uptake
- The depth of soil containing 90% of the roots of a plant of that size

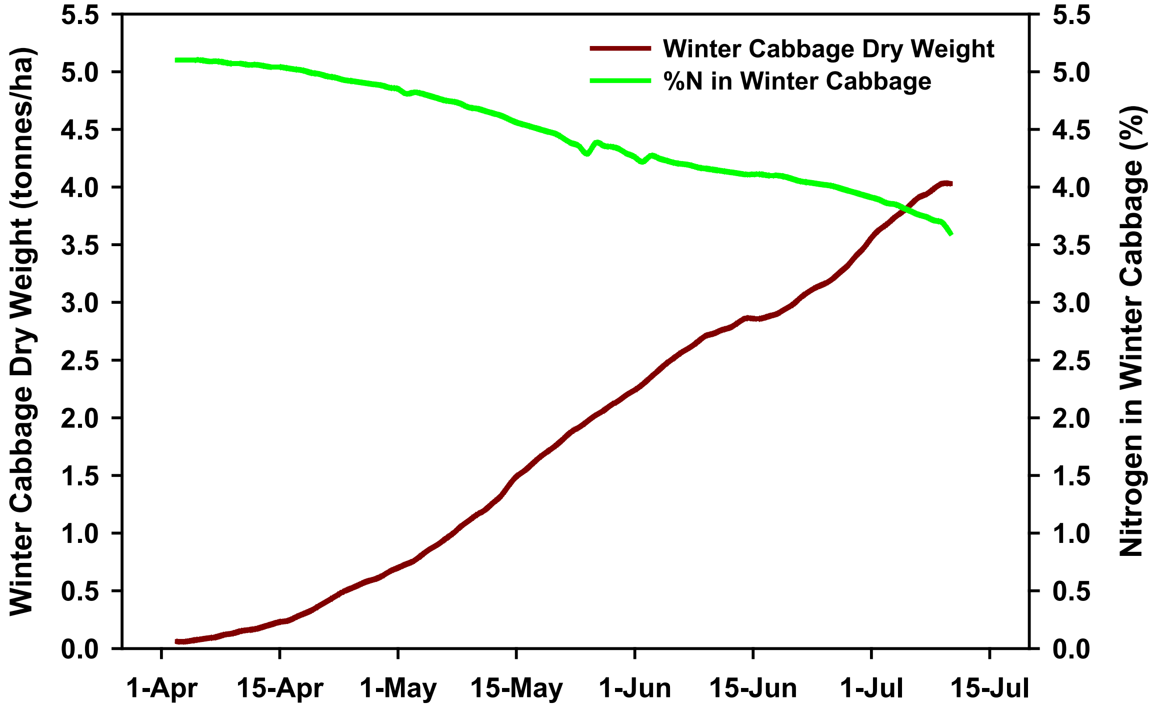

Figure 3.2.2.5 Changes in dry weight and %N of winter cabbage across the season.

Soil water balance - Evapotranspiration and distribution of soil water

Transpiration is calculated using fractional crop cover, the rate of evaporation from an open water surface, and the amount of water in the rooting zone. Evaporation from bare soil likewise depends on soil water distribution down the profile and on the evaporative conditions. Specifically, all calculations start from an initial value of soil moisture deficit (D_{sm}). Total daily evapotranspiration, E_t (cm), is calculated from:

$$E_t = (1 - F_P)\ E_S + (F_P\ E_P) \qquad \text{(Eq.6)}$$

where:

F_P: is the fraction of soil surface covered by plants
E_S: is the evaporation rate (cm/d) per unit area of bare soil
E_P: is the daily transpiration per unit area of soil covered by plants

E_S is calculated by assuming that the rate of loss of water from bare soil declined in a negative exponential manner with increasing cumulative soil moisture deficit in the bare soil with corrections for intermittent rainfall.

Consequently; $E_P = 0$, when $D_{sm} \geq D_{pwp}$

Where:

D_{pwp}: is the soil moisture deficit to the depth of rooting at the permanent wilting point.

The water balance model in N-ABLE function as follows. Evapotranspiration (E_t) draws water first from the surface layer until the water content reaches permanent wilting point and then water is drawn from the next layer and so on down the profile (Figure 3.2.2.6). Likewise, water gained by rainfall or irrigation is added to the first layer until this reaches field capacity and then moves to the next layer, and so on down the profile (Greenwood *et al.,* 1996).

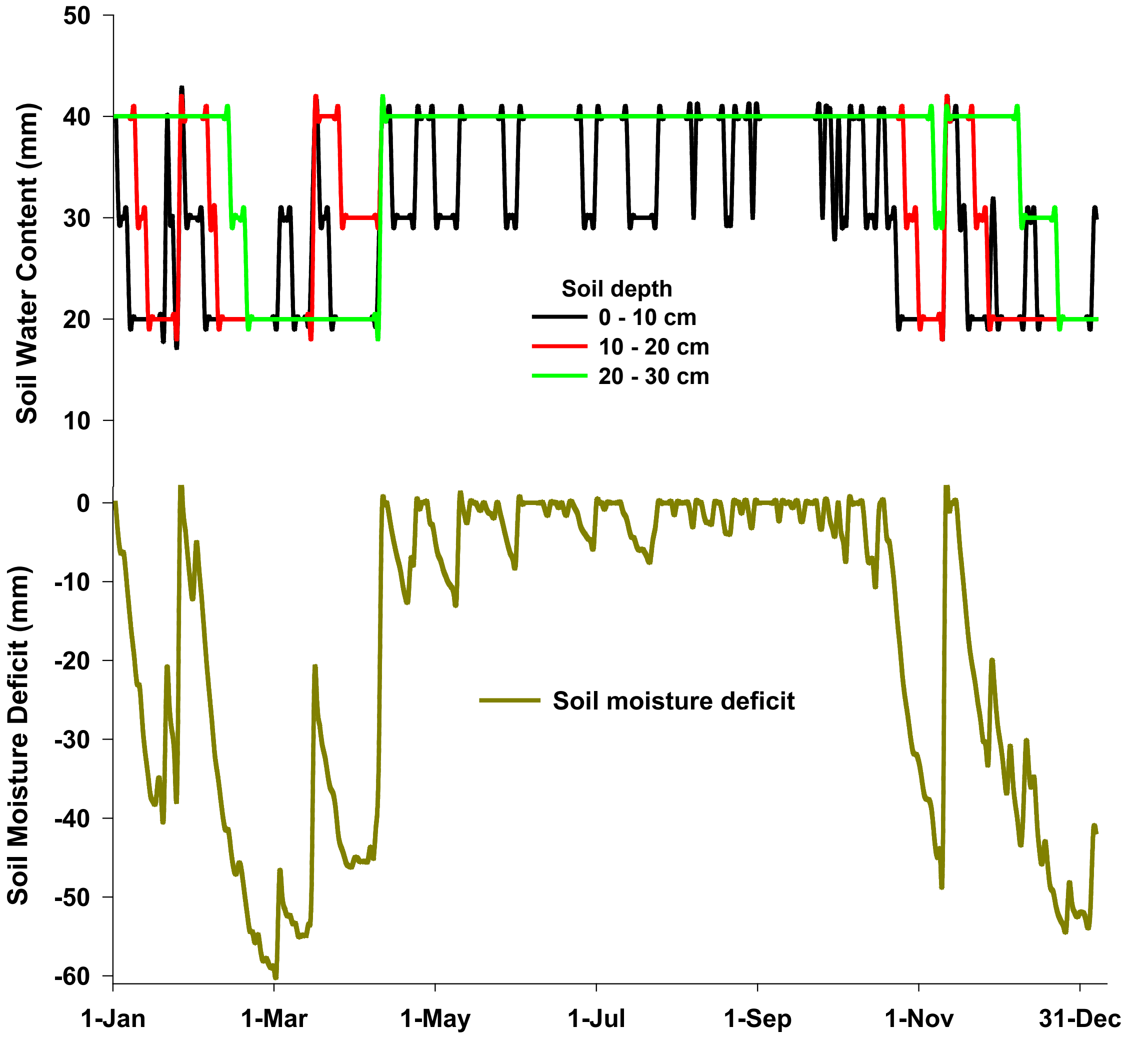

Figure 3.2.2.6 Soil water balance for three upper soil layers and the soil moisture deficit throughout the soil profile for Patumahoe clay loam soil under bare soil fallow conditions.

Figure 3.2.2.7 shows an example with predicted values by N-ABLE of soil moisture deficit (SMD). The two lines represent the SMD from the same soil under bare conditions and when planted with potatoes on the 1st of October. The area between the two lines in the figure represents the loss of water through transpiration. The soil type and weather data under study was a Patumahoe soil located near the Pukekohe area for the year of 2000. The moisture deficits in the bare soil occur through evaporation but in the soil planted with a crop occur through evaporation of the soil plus transpiration of the plant (Evapotranspiration). As expected, the evapotranspiration of water from the planted soil is higher than for the bare soil. This may become an important management decision for soils left fallow in wet areas because lower evaporation may result in greater drainage and increased leaching of nitrate. For example, the bare soil (Figure 3.2.2.7) reaches field capacity (zero soil water deficit) on 5 days in April, whereas the planted soil does not reach field capacity until May.

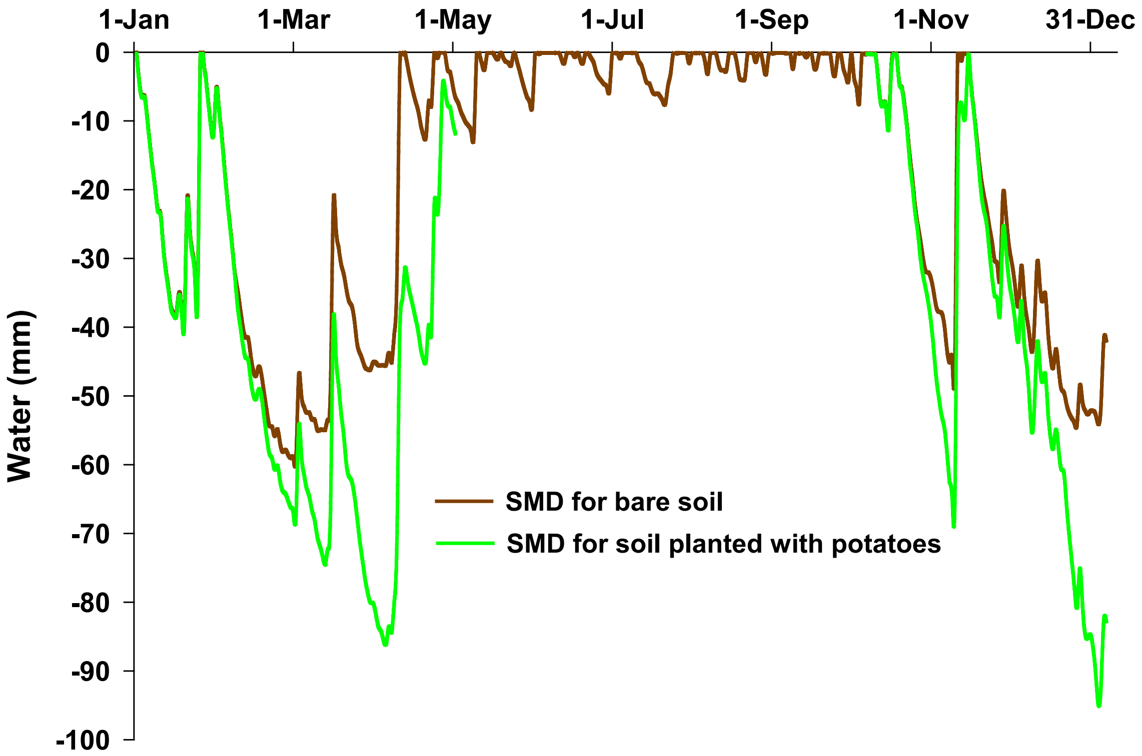

Figure 3.2.2.7 Simulated soil moisture deficits for the Patumahoe clay loam (2000) left bare or planted with potatoes on the 1st of October.

Crop residues

The type and amount of residues that are incorporated into the soil before planting a crop has a big impact on the fertiliser recommendation. If the carbon/nitrogen ratio (C:N) of the crop debris is high, then the crop residue breakdown results in a temporary disappearance of soil-mineral-N by immobilization into newly formed soil organic matter. The rate of soil residue breakdown is then limited by the amounts of N in the soil. If the crop residue C:N ratio is low, decomposition results in the release of N into the soil by mineralization. So the C:N ratio of the crop residues plays an important role on determining the effects of their decomposition on the N dynamics of the soil. Figure 3.2.2.8 illustrates the immobilisation/mineralisation processes when crop residues are ploughed into a Patumahoe soil. The amounts of soil mineral N (0–90 cm) were simulated using the N-ABLE model. In the bare soil without residue incorporation (black colour line) soil mineral N increases from the date of cultivation due to mineralisation of soil organic matter only. The incorporation of 10 tonnes of DM/ha of a high C:N residue (green colour line) causes less N to be net mineralised because in order to decompose the carbon rich residue soil bacteria and fungi require additional N. The consequence is that some nitrate mineralised from the soil organic matter is utilised by the population of bacteria and fungi growing on the high C:N residue. The incorporation of 10 tonnes of DM/ha of a low C:N residue (red colour line) causes greater N mineralisation as bacterial and fungal decomposition of this N rich residues releases more nitrate. Table 3.2.2.2 show examples of some C:N ratios of cover crops.

Table 3.2.2.2 Examples of C:N ratios of cover crops

Organic Material	**C:N ratio**
Young rye plants	14:1
Rye at mid-boot stage	40:1
Hairy vetch	10:1 to 15:1
Crimson clover	15:1
Corn stalks	60:1
Wheat straw	80:1 to 100:1
Sawdust	250:1

Source: Adapted from ATTRA, 2001. Overview of cover crops and green manures.

The large reduction in soil mineral N in June results from winter leaching. In June alone there was 130 mm of cumulative drainage with average nitrate leaching of 155, 82, 63 kg N/ha in the low C:N residue, bare soil and high C:N residue treatments respectively.

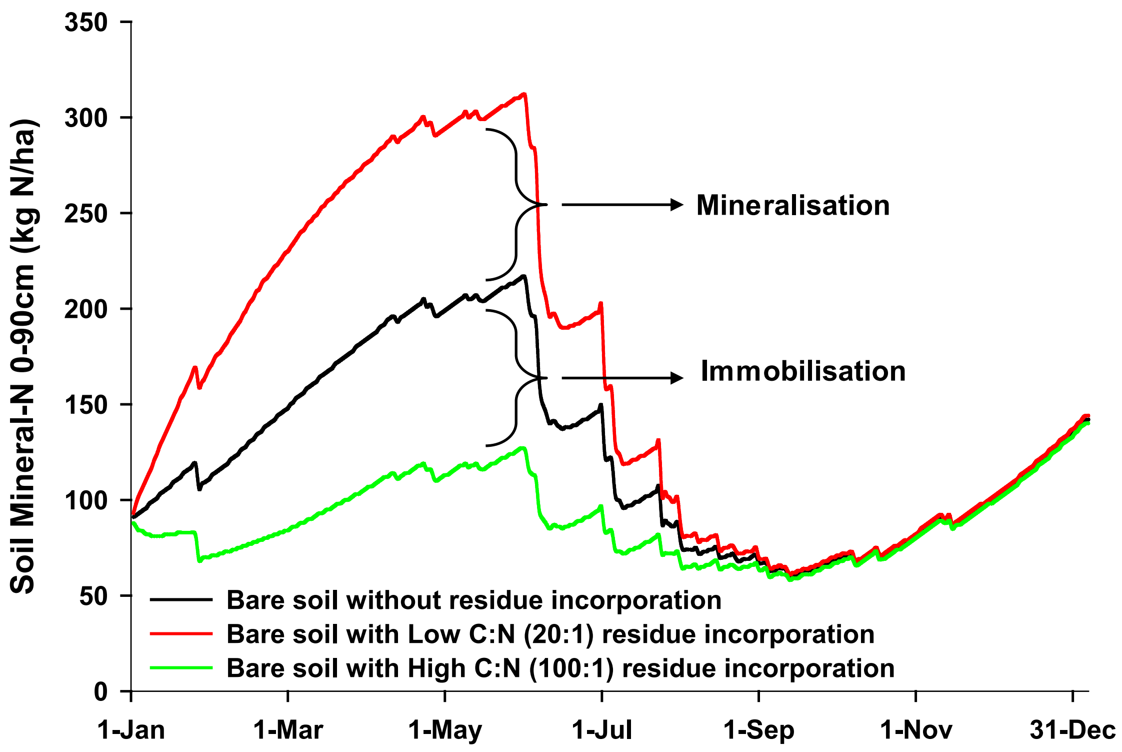

Figure 3.2.2.8 The influence of decomposition of soil organic matter and crop residues with different C:N ratios on the amount of soil mineral-N. N-ABLE simulation.

One limitation of the N-ABLE model is that mineralisation rate is not moderated by soil moisture content.

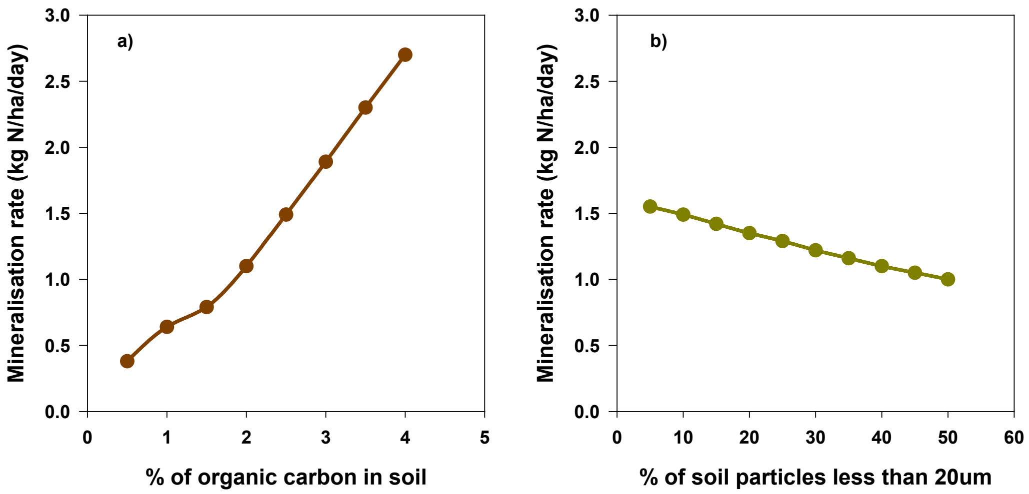

Figure 3.2.2.9 The effect of organic carbon and particles <20 µm on the mineralisation rate of organic matter.

As mentioned earlier, mineralisation rate is also dependent on soil temperature. If the plant material incorporated in the soil contains a lot of N, decomposition results in the release of mineral-N. Breakdown rate is then limited by temperature.

If the incorporated plant material has a high C:N ratio and there is low N in the soil breakdown proceeds at a slower rate because there is insufficient N for bacteria and fungi to decompose the organic material. Breakdown then proceeds as fast as the input of mineral-N from mineralisation of soil organic matter (Greenwood *et al.*, 1996).

Applications of dynamic models

Dynamic crop models may be inaccurate in predicting actual crop yields and N requirements, but their real strength is in supporting decisions on the amount and timing of fertiliser N application. For example, in some areas of NZ, the maximum amount of N applied at any one time or the total amount of fertiliser N in a year may be restricted (due to environmental guidelines). Timing and placement of fertiliser will then have to be optimised in order to improve the efficiency of the limited N available. Computer models such as N-ABLE or potato calculator may have a role in designing such guidelines. Fertiliser recommendation systems incorporated into computer models have a number of advantages as they allow a more objective interpretation of data (such as calculation of leaching losses of nutrients) and they allow repeatable calculation of fertiliser requirements of crops. This is particularly important if abnormal climatic conditions occur and N side-dressing requirements need recalculating. To illustrate this application the N- ABLE model is used in sections 3.2.3 and 3.2.4 to illustrate how different management scenarios influence the winter leaching of NO_3^-.

Summary

Advances in fertiliser technology have made it economically feasible for modern crop producers to essentially eliminate N deficiencies during crop production. Fertiliser N is normally applied at above optimal rates. The key N management problem today is learning how to use N fertilisers to maximize the benefits for producers while minimizing environmental problems. Future efforts to improve management practices will require the use of diagnostic tools that reliably measure levels of N excess as well as N deficiencies. Mounting evidence suggests that crop and livestock producers cannot afford the economic and environmental cost of not conducting routine annual evaluations of N management practices on their fields. The use of dynamic models that consider soil-plant-climate interactions are becoming popular and can be used as agricultural tools to improve fertiliser recommendations for arable crops as well as maintaining the surrounding environment without damaging it.

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3.2.3 Winter nitrate leaching from vegetable production

Key Learning Objectives

After studying this section you should:

1. Be aware of recent research into nitrate leaching in arable systems.
2. Be able to describe soil and crop management practices that would be helpful at reducing winter leaching of nitrate from arable systems.

Introduction

Monitoring of ground water quality continues to show general trends of increasing nitrate levels in ground water. This issue is becoming more widespread and, consequently, is attracting greater attention from the general public.

According to the New Zealand Ministry of Environment web site (http:www.mfe.govt.nz) areas around Waimea plains, Tasman, Lincoln, Ashley catchment, Pukekohe, Hamilton lowlands, Hauraki lowlands, Takapau plains, Heretaunga plains, Tokoroa, and Manawatu have some well waters that exceed the maximum allowable value for NO_3^--N in ground water.

Elevated levels of NO_3^--N in ground water can lead to increased concentrations of NO_3^--N in drinking water. Public perception is that these elevated nitrate concentrations are sufficient to cause the human health problem called methaemoglobinemia, which reduces the ability of blood haemaglobin to carry oxygen. Young infants ("blue baby syndrome"), pregnant women and people with certain specific enzyme deficiencies are more susceptible to this health condition.

Surface water quality

Apart from the human health hazard of groundwater contamination, elevated drainage water nitrate concentrations can have detrimental environmental effects on surface water quality. In recent times "Environment Waikato" has indicated that land use planning will be used to minimise the amount of N in drainage waters entering Lake Taupo (See Module 4 on Nutrient Trading). Extra N in the lake encourages the growth of algae in the water. These algae reduce the water clarity that Lake Taupo is famous for. The belief is that the extra N entering Lake Taupo is from increased N leaching from farmland.

Loss of costly nutrients

Loss of N by leaching can have a significant negative impact on farm productivity, as most of the New Zealand agricultural soils are N deficient. So loss of N from agricultural soils through leaching also represents an economic loss. When drainage water N concentrations are elevated to 20 g NO_3^--N/m^3 then 100 mm of winter drainage will leach 20 kg N/ha. In 2004 this represents a urea fertiliser cost of approximately $20/ha.

Soil water balance – winter drainage

Drainage dominantly occurs in the winter and early spring period. This is when the evapotranspiration loss is low (1 to 1.6 mm/day) thus rainfall events easily recharge the soil to zero water deficit. Rainfall occurring when the soil water deficit is zero generates drainage and runoff. Figure 3.2.3.1 shows the distribution of rainfall, soil moisture deficit, and drainage for the year of 2000 in Pukekohe. The rainfall was measured in a weather station near Pukekohe and soil moisture deficit and drainage were simulated by N-ABLE. There were no crops planted in the field and the soil was left fallow the whole year. The total rainfall was 1205 mm and the cumulative drainage throughout the year was 690 mm. The 2000 winter was very wet, particularly the months of June, July and September. During these months, there was very little soil water deficit. There were 38 drainage events throughout the winter and a total of 334 mm of cumulative drainage. Figure 3.2.3.1 will be utilised throughout this section to discuss the potential effect that winter drainage can have on nitrate leaching.

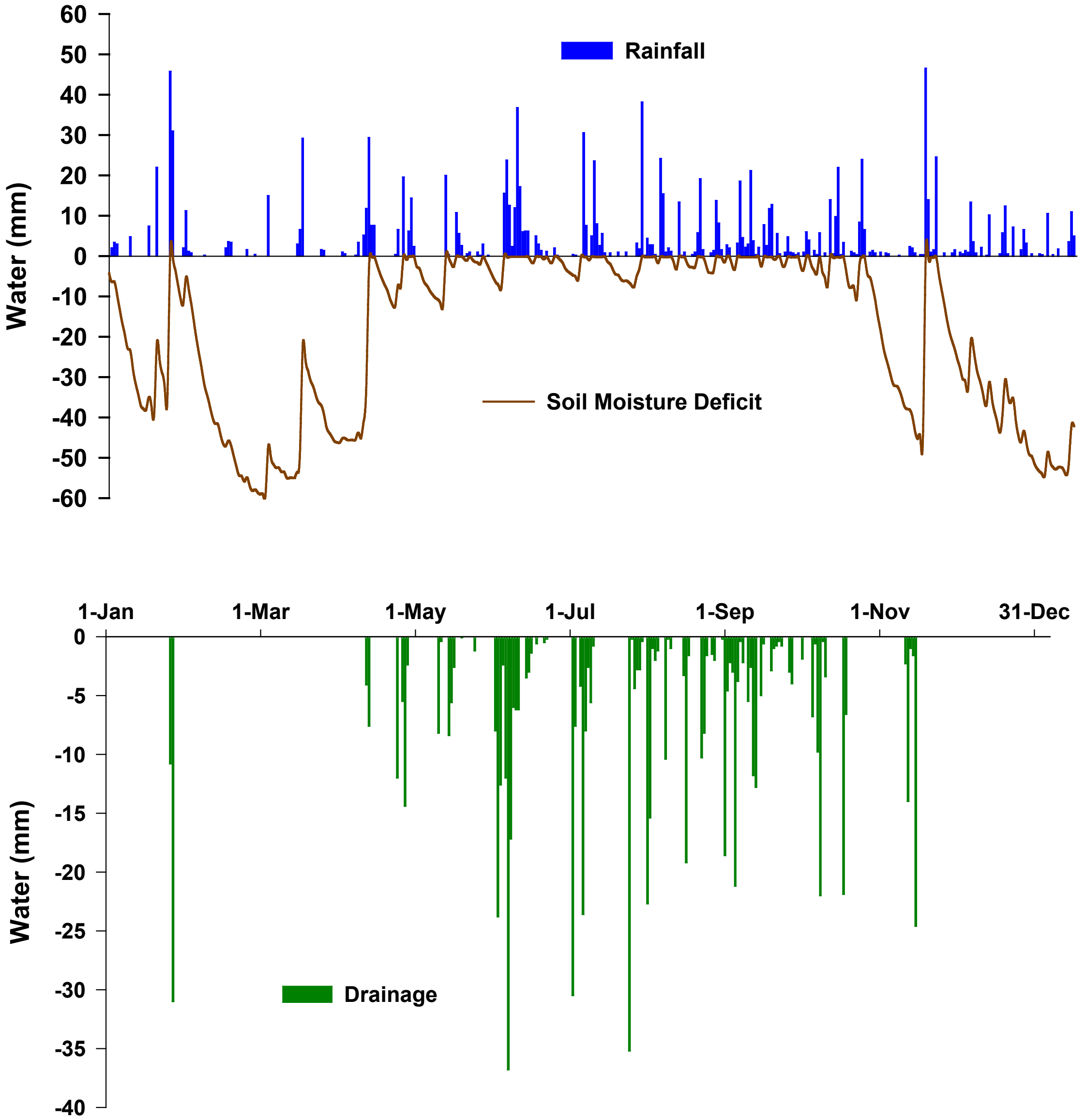

Figure 3.2.3.1 Soil water balance for the year of 2000 in Pukekohe.

Impacts of land use and crop management

In this section, we examine the influence of some landuse and crop management strategies on nitrate leaching. Nitrate contamination of groundwater in New Zealand can result from intensive dairy farming in some regions and from winter vegetable production in other areas. Most of the N that leaches from dairy pastures originates from the urine patch areas, where the high N concentrations are greatly in excess of pasture plant requirements. In contrast, NO_3^--N that is leached from winter vegetable crops largely originates from either applied N fertiliser, or from the breakdown of post-harvest crop residues. High rates of N fertiliser are often applied to these crops in an attempt to overcome their slow growth rates during winter. Yields are often increased by these high fertiliser rates, although fertiliser recovery rates are often low, leaving large amounts of N in the soil that are susceptible to leaching (Martin, 1995; see also the previous sections 3.2.1 and 3.2.2 on N cycle for arable crops and N fertiliser requirements of arable crops). The return of large amounts of post-harvest plant residues also contributes to the high leaching potential under vegetable cropping. The returned residues usually have low C:N ratios and mineralise rapidly when incorporated, resulting in the accumulation of large amounts of NO_3^--N in the soil (Greenwood *et al.*, 1996; see also the previous section on N fertiliser requirement of arable crops). Therefore, it is important to identify ways of managing N in vegetable crop production, particularly in winter in order to minimise ground water contamination through NO_3^--N leaching. Reducing N leaching has both economic and environmental benefits: the grower wins by applying less fertiliser and the environment wins through less nitrate contamination in water.

The aim of this section is to introduce potential management options to minimise winter NO_3^--N leaching from land used for vegetable cropping. Two situations are studied in which the high N requiring crop potatoes are grown either in summer conditions (latitudes south of Waikato) or winter condition in frost free areas (north of Waikato).

Spring – summer crop followed by fallow soil

In this scenario, the crop is removed before the soil begins to dry out in summer. The soil is then left fallow. Leaving the soil in a fallow period when no crop is being grown and land is kept clean of weeds is a common practice in some areas of NZ. The reason for fallow periods is usually either to reduce the weed population or, in drier regions, to allow time for recharge of soil water. However, several disadvantages occur when the soil is left fallow. A pivotal disadvantage during the fallow period is that there is no input of organic matter. The decomposition of residues and native soil organic matter continues over time causing a net loss of soil organic matter. In addition, the surface is unprotected and exposed to raindrop impact, which can lead to soil capping and possible erosion. With no crop in place to take up soil N, a soil left fallow presents a major risk of N leaching during the year. Figure 3.2.3.2 shows simulated values (from N-ABLE) of N that are leached from a bare soil left fallow and with initial soil mineral-N of 30 kg N/ha. It is noteworthy that the N leaching follows the same pattern as the drainage events (see Figure 3.2.3.1) and most of the leaching occurs during the winter period. N-ABLE predicted a total of 303 kg N/ha leached below 90 cm during the year of 2000 from a field near Pukekohe. As we will discuss later a highly recommended management practice is to plant cover crops to minimise potential nutrient leaching. The cover crop will take up and store N over winter when soil NO_3 is prone to leaching below summer crop root zones.

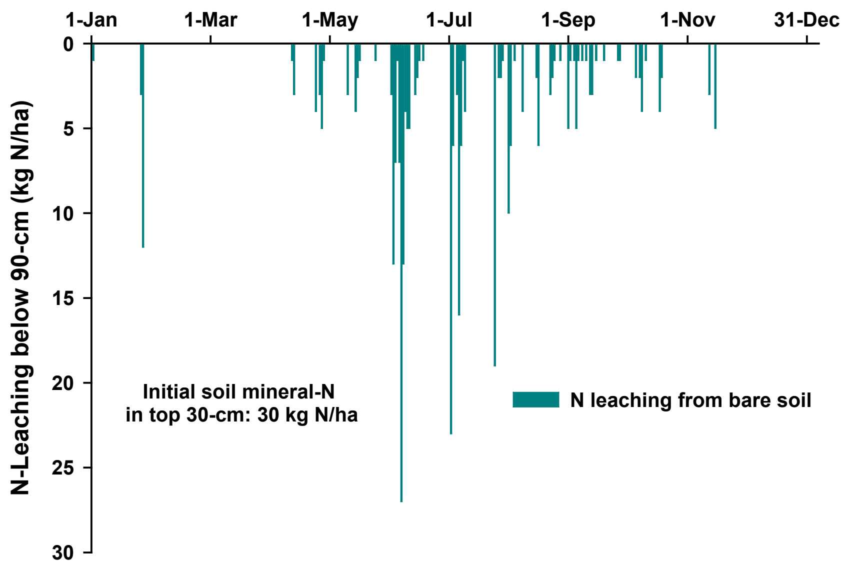

Figure 3.2.3.2 Nitrogen leaching from a bare soil near Pukekohe.

Summer crop (potatoes) followed by winter fallow

In Manawatu most of the potato cultivation is carried out during summer to autumn. Normally planting starts September to October and harvesting is around May/June. Farmers are adopting different land use practices during winter period and they are discussed below in relation to winter N leaching.

A late potato harvest may result in cattle being used to eat the residual potatoes and then the ground is left fallow until early spring planting. With no crop in place to take up soil N, a winter fallow strategy presents a major risk of N leaching during winter. The soil mineral N produced from the breakdown of residues from the previous harvest, and fertiliser N left unused by the plant are readily leached during drainage events. So, if fallowing is the practice to be adopted, care must be taken to minimise the residual mineral N remaining in the soil after potato harvest in autumn. One way to achieve this is by matching the timing and rates of N inputs to the pattern of crop N uptake. Painter and Augustin (1976) reported that N uptake by a potato crop was completed 2-3 weeks before the start of canopy senescence. Results from experiments conducted by Martin (1995) and Sher (1997) (Figure 3.2.3.3) show that this period is around 90-110 days after planting (DAP). Therefore, N fertiliser application should be planned during crop emergence and to be completed well before 90-110 DAP.

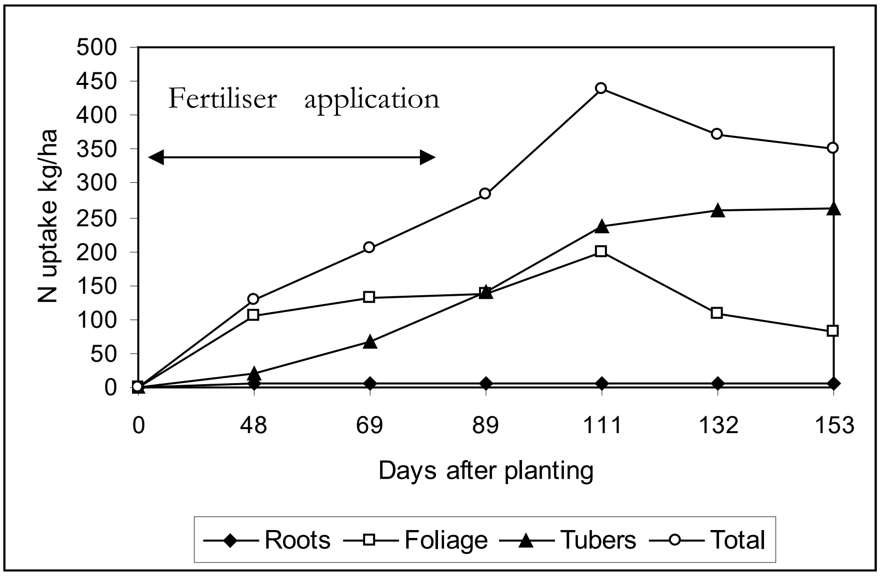

Figure 3.2.3.3 Nitrogen uptake (kg/ha) by 'Fiana potato roots, foliage and tubers from planting to maturity; BASF Field study at Fielding (Sher, 1997).

Summer crop followed by winter vegetable crop

After the potato crop harvest, growing a vegetable crop such as Broccoli is another option during the winter period. As well as the commercial value of this crop it can also be used to derive environmental value if the crop can be managed to utilise the N left in the soil from the previous summer/autumn crop thereby reducing N leaching. Williams and Tregurtha (2003) demonstrated that it is possible to reduce N leaching from soils under a winter broccoli crop by matching the fertiliser N input and available soil N at planting (Table 3.2.3.1). Site 2, in the trial had higher available soil N at planting than the site 1. The soil N was not considered in planning fertiliser applications and the same amount of fertiliser N input was applied to both sites. The result was that N leaching increased by 80 kg N/ha at Site 2 compared to site 1 and there was little impact on Broccoli yield.

Table 3.2.3.1 Effect of available soil N at planting of a Broccoli crop on winter N leaching (based on data of Williams and Tregurtha, 2003)

Measurement	Site 1	Site 2
Yield (t DM/ha)	2.6	2.8
Soil mineral N at planting (kg N /ha)	39	84
N fertiliser inputs (kg N/ha)	59	59
N removed in crop (kg N/ha)	21	25
Drainage (mm)	111	94
Nitrate leached (kg N/ha)	11	91

The use of transplanted vegetable crops creates a lower overall need for fertiliser, because part of the critical need at the early stages is met in the nursery production. However, there are large variations between the vegetable crops, with some having very low or no N requirements. The range of crop N needs is illustrated in Table 3.2.3.2

Table 3.2.3.2 Range of vegetable crops N requirements (Wood, 1997)

Nitrogen need (kg/ha)	Crops
Very low (0-50)	Kumara, Peas, Beans
Low (50-100)	Carrots, Beetroots, Corn
Medium (100-200)	Curcurbits, Summer lettuce, Cauliflower
High (200-300)	Winter Cauliflower
Very high (300+)	Winter potatoes, lettuce, cabbage

Ideally, crops with high N demand can be managed with autumn plantings to take up residual soil N initially, followed by N side-dressings that have high uptake efficiencies thus minimising N loss.

Summer crop followed by winter cover crops

Another land use option is planting cover crops after autumn potato harvests for growth during the winter. A range of frost tolerant species can be grown as cover crops. When species like cereals and grasses (see Table 3.2.3.3) are grown, dry matter yields in excess of 8 t/ha can be produced over the winter, resulting in significant uptake of mineral N from the soil over winter and in spring they can return large quantities of organic matter to the soil. The consequence is that winter leaching losses of nitrate can be reduced (Williams and Tregurtha, 2003). When winter cover crops are ploughed down, the N in the residues is released by decomposition and can become available to the subsequent spring planted crop.

Table 3.2.3.3 Yield of winter cover crops and amount of nitrate leached at Aorangi, Manawatu (Williams and Tregurtha, 2003). NM= not measured

Cover crop	Yield (t DM/ha)	Amount of nitrate leached kg N/ha
Doubletake triticale	17.8	NM
4723.4 triticale	15.3	13.3
Hokonui oat	14.3	NM
Stampede oat	13.7	20.5
Apollo Italian Ryegrass	8.3	28.9
Apollo+vetch	9.9	17.6
Apollo+white clover	11.0	18.8
Yellow sweet clover	4.8	32.5
Blue lupin	5.7	41.1
Red clover	3.7	50.5
Fallow	5.0	37.6

Fowler *et al.* (2004) reported that green manure crops can reduce the amount of N leaching over winter compared to fallowing. In an experiment located adjacent to Lincoln University, they found that at the end of the green manure crop period, the cumulative N loss from the green manure treatments (4.1-4.9 kg N/ha) was half of that determined from the fallow treatment (8.4 kg N/ha). The amounts of N taken up by the green manure crops were 100, 162 and 126 kg N/ha for oats, lupins, and oats-lupins respectively. It is noteworthy that the cumulative amount of N leached from the fallow treatment in this experiment was very low compared with N losses reported in other studies (23 to 106 kg N/ha, Francis *et al*., 1994 and Francis *et al*., 2003). The reason for this discrepancy is that the soil used in this study has been under organic cropping for 3 years with no inputs of soluble N fertiliser. Francis *et al.* (1994) study used soils after the incorporation of 2-4 years old pasture in autumn where large quantities of N would have mineralised. Subsequent to this experiment, annual rye grass was sown 3 weeks after green manure incorporation to study the effect of dry matter yield and N uptake. Rye-grass was harvested 6 weeks later and yields were lower than expected due to weather conditions. Nonetheless, they observed that dry matter yield and N uptake by rye grass were significantly greater (45% more DM/ha and 50% more N uptake/ha) for the green manure amended soil than for the fallow treatment.

These results indicate that improved N use efficiency can be gained by using a winter cover crop. The supply of N to the spring crop from the decomposition of ploughed-under winter crop residues will reduce the fertiliser N input in spring.

Effect of fallow, type of residue and cropping on N leaching

Management of winter N leaching in mixed cropping systems (pasture/arable) is becoming increasingly important as attention is focused on non-point sources of nutrient pollution. Generally as explained in section 3.2.2 the first year following ploughing-in of a pasture, fertiliser N is usually not required by arable crops to achieve maximum yield due to high levels of soil mineral-N. However, a pivotal disadvantage of mixed pasture-arable systems is the potential amount of NO_3 that can be leached.

Post-harvest nitrate leaching may occur when unused fertiliser applied to summer crops accumulates or when crop residues rapidly mineralise following summer harvesting. The build-up of residual soil NO_3 is then susceptible to winter leaching. Late summer–sown cover crops can serve as NO_3 catch crops that absorb and store N over winter when soil NO_3 is prone to leaching below summer crop root zones.

There are several possible strategies for reducing the accumulation of nitrate in the profile prior to winter leaching events. For example, Francis *et. al.* (1994) proposed three different management practices:

a) Delaying ploughing-in pasture until late winter/early spring to minimize the period for mineralisation
b) Sowing winter rather than spring cereals
c) Using a winter cover crop

Based on the potential benefit of these practices in reducing N leaching Francis *et al.* (1994) investigated the accumulation of NO_3 in a Templeton silt loam soil profile. They reported that mineralisation of organic matter increased with increasing fallow period between ploughing and leaching. Specifically, the total amount of N accumulated in the profile by the start of winter was 107-131 and 42-45 kg N/ha when a 4-year-old pasture was plough-in March or May respectively. Cumulative leaching losses over the first winter following pasture incorporation were greater from March fallow (72-106 kg N/ha) than May fallow (8-52 kg N/ha) (Figure 3.2.3.4). The two year study show that cover crops were ineffective at reducing leaching losses in one year (rainfall over autumn/winter was 344 mm) but reduce losses by 60% in the second year where rainfall was much greater (rainfall over autumn/winter was 546 mm). They also reported that incorporation of large amounts (>7 t/ha dry matter) of greenfeed oats residues in spring caused depressions in both yield and total N uptake of wheat crop, largely due to net N immobilisation.

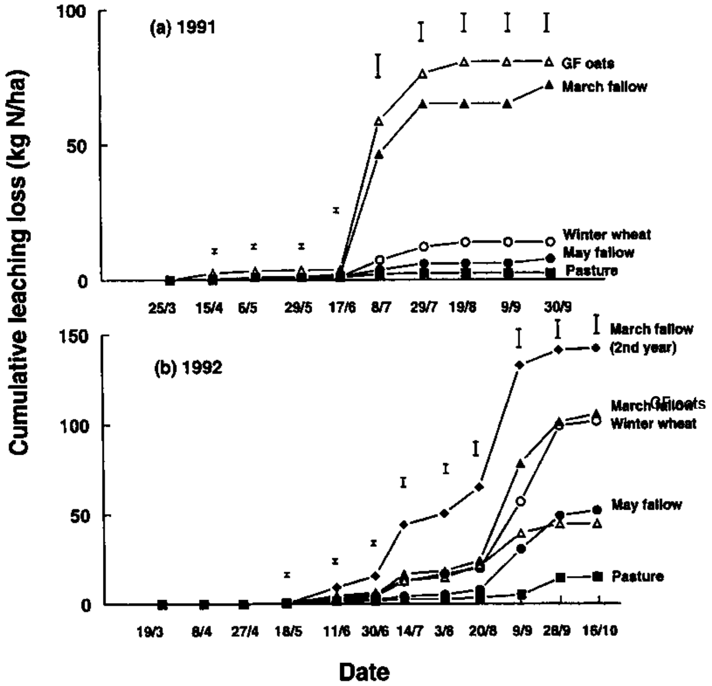

Figure 3.2.3.4 Cumulative nitrate leaching losses from March fallow (▲), greenfeed oats (Δ), May fallow (●), Winter wheat (○), pasture (■) over the first autumn/winter in (a) 1991 and (b) 1992. Losses over the second autumn/winter following March fallow (♦) are also shown. Vertical bars represent S.E. (Francis et.al. 1994).

Based on the management practices proposed by Francis *et al.* (1994) we use N-ABLE to simulate six different management scenarios to illustrate their influence on the amount of N leached. Three scenarios consider the effect of wheat straw residues (100 C:N ratio) and hairy vetch residues (20 C:N ratio) and on a bare clay loam soil when incorporated on March 1st. The other three scenarios consider the same type of residues when incorporated in a March 1st cultivation and winter broccoli planted on April 10th, with and without N fertiliser application.

In summary the different management scenarios created were:

a) Bare soil, with no residue incorporation (No-till situation)
b) Bare soil, incorporating 7 tonnes of DM/ha of a 100 C:N residue
c) Bare soil, incorporating 7 tonnes of DM/ha of a 20 C:N residue
d) Planting a winter broccoli crop, incorporating 7 tonnes of DM/ha of a 20 C:N residue, no fertiliser
e) Planting a winter broccoli crop, 7 tonnes of DM/ha of a 100 C:N residue, 250 kg N/ha
f) Planting a winter broccoli crop, incorporating 7 tonnes of DM/ha of a 20 C:N residue, 250 kg N/ha

To begin with, consider the climatic conditions presented in Figure 3.2.3.1. During summer and early autumn, there is a significant soil water deficit and no significant drainage events occur. However, the soil is sufficiently moist that mineralisation/immobilisation of residues occur. On the other hand, during winter and early spring, there was very little soil water deficit. On average, there were 38 drainage events throughout the winter and a total of 334 mm of cumulative drainage. It is important to remember that N leaching follows the same pattern as the drainage events and consequently most of the leaching occurs during the winter period.

Figure 3.2.3.5 a, b, and c shows that even when the soil is fallow and no cropping or N fertiliser is applied there is a significant amount of N that is leached (231 to 403 kg N/ha/year). Nitrogen leaching from a bare soil with no residues incorporation was 303 kg N/ha/year and most of the N coming from mineralisation of soil organic matter. When 7 tonnes of DM wheat straw residue with 100 C:N ratio is incorporated in March, the amount of leaching was significantly reduced (231 kg N//ha/year) and the reason for this reduction is that there is a net immobilisation of N by soil bacteria and fungi. The opposite effect happens when 7 tonnes of DM residue with 20 C:N ratio is incorporated and mineralisation of soil organic matter releases N that is readily available to leach (403 kg N/ha/year Fig 3.2.3.5 c). In this situation the accumulation of mineral-N in the soil profile following the cultivation of vetch hairy residues was likely to have occurred through the net mineralisation of organic-N derived from both hairy vetch residues and readily-mineralisable soil organic matter.

Figure 3.2.3.5 d, e, and f shows the amount of N that is leached in a clay loam soil where we planted a winter broccoli with and without fertiliser application. In Figure 3.2.3.5 d winter broccoli was sown in April without fertiliser but incorporating in March residues with low C:N (20:1). In this case, the N uptake of winter broccoli reduces the soil mineral N content at the start of the winter drainage events reducing the amount of N leached (334 kg N/ha/year). The highest leaching losses of nitrate (540 kg N/ha/year) were obtained when hairy vetch residues were incorporated in March, winter broccoli was sown in April and 250 kg N/ha was applied at planting time (Figure 3.2.3.5 f). Nitrogen leaching below 90 cm shows and increases as the net sum of the nitrate generated by soil organic matter mineralisation plus fertiliser N became greater than the rate of winter broccoli N uptake. Leaching losses such as 540 kg N/ha/year are substantial both in terms of economic loss to the farmer and their detrimental effect on ground water quality. Incorporating residues of high C:N as well as splitting N fertiliser application to match crop demands appears the most reliable approach to reducing winter leaching losses.

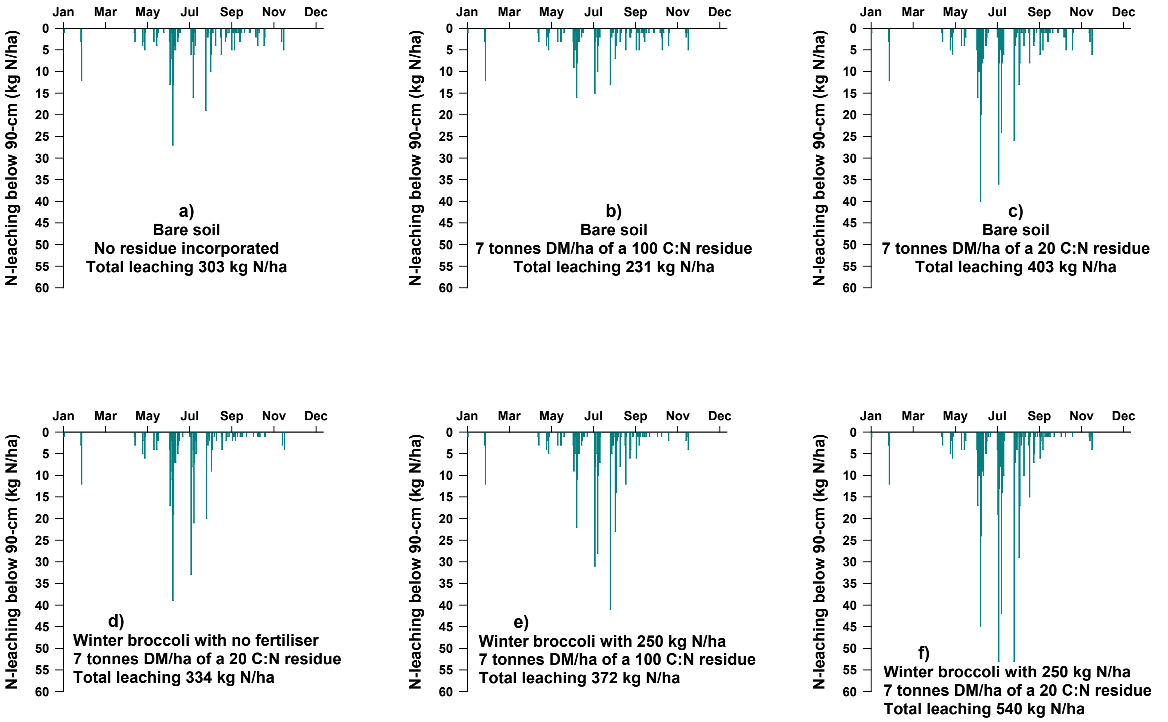

Figure 3.2.3.5 Effect of fallow, residue incorporation, and winter broccoli (planted April 1) on N leaching.

Measuring and managing N supply

Testing the amount of soil mineral N at planting

As shown in Table 3.2.3.1 for winter Broccoli crop it is prudent to test the residual N levels at planting and these levels should be taken into account when calculating the N fertiliser requirements of the next crop. High test levels can offset the amount of fertiliser N required (see Broccoli discussion above and previous section on N fertiliser requirement of arable crops).

Reducing the amount of fertiliser N applied at the time of planting

Crops need some N for establishment however; applying more N than can be taken up by the small plant root systems is inefficient. Typically, current fertiliser practice for winter potatoes in Pukekohe is 469 kg N/ha applied as 319 kg N/ha at planting and 150 kg N/ha applied as side dressings eight weeks later (Williams and Tregurtha, 2003). The data from an experiment conducted on a winter potato crop at Pukekohe (Table 3.2.3.4) shows that reducing the amount of N at planting by 200 kg N/ha had little effect on yield, but reduced the amount of N leached by 60 kg N/ha. Similar results have been obtained with other potato (Martin *et al.*, 2001; Williams *et al.*, 2000) and spinach (Williams *et al.*, 2003) crops.

Table 3.2.3.4 Effect of N input at planting potato (based on Williams and Tregurtha, 2003)

Measurement	Pukekohe (Site 1)	Pukekohe (Site 2)
Yield (t/ha)	28	26
Soil mineral N at planting (kg N /ha)	41	46
N inputs (kg N/ha)	319	109
N removed in crop (kg N/ha)	108	103
Drainage (mm)	373	373
Nitrate leached (kg N/ha)	171	111

Nitrogen rate required for winter crops

Although several studies were conducted in Pukekohe, researchers have yet to establish minimum rates of N required by winter grown potato crops in Pukekohe, or any other region. Therefore, it is growers and fertiliser consultant's responsibility to make the decision based on residual soil N, mineralisable N and crop N requirement (see previous section on N fertiliser requirement of arable crops).

The work done by Martin *et al.* (2001) clearly revealed that potato crop required some starter N fertiliser. However, under their experimental conditions they found that there was no yield advantage in applying more than 242 kg N/ha (Tables 3.2.3.5 and 3.2.3.6). Even this rate appeared to be too high, as there were still significant quantities of mineral N remaining in the soil at harvest, and N leaching losses were double the amount leached from the control treatment (Table 3.2.3.6). The N leaching losses at the rates of 350 and 472 kg N/ha were higher than that at the rate of 242 kg N/ha.

Table 3.2.3.5 Rate and timing of N fertiliser application used in Martin et al. (2001)

Treatment (kg N/ha)	Application Date			
	2 May	14 Jun	10 Jul	3 Aug
0	0	0	0	0
472	300	172	0	0
350	180	57	57	57
242	150	46	46	0

Table 3.2.3.6 Effect of fertiliser rate on potato yield, maximum plant N uptake and amount of leaching (Martin et al., (2001)

Treatment	Yield (DM t/ha)	Maximum plant N uptake (kg N/ha)	Amount of N leached (kg N/ha)
0	3.3	38	82
472	4.4	130	208
350	4.4	124	219
242	3.8	123	167

Summary

In this section we have introduced you to New Zealand research literature on nitrate leaching from crops in winter and spring drainage. We have shown you how it is possible to simulate these leaching losses with mechanistic computer models. Models which can then assist in designing strategies to reduce the losses of N by leaching by varying soil, crop and fertiliser management practices.

Activities

Readings

We suggest you now read the five research papers that make up the readings 3.21 –3.25 (page 3.89 onwards). Make additional notes where you think appropriate.

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Reading 3.3.1

Williams, P.H., and Tregurtha, C.S. 2003. Managing nitrogen during winter in organic and conventional vegetable cropping systems. *Agronomy New Zealand, 32*: 61-67.

Managing nitrogen during winter in organic and conventional vegetable cropping systems

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Abstract

Intensive vegetable crop rotations require inputs of nitrogen (N) to maintain high levels of production and crop quality. Managing N over the winter period is often the most difficult as plant growth is slow and the potential for nitrate leaching is high. Comparisons of N inputs and outputs in a range of winter crops showed that inputs usually exceeded N outputs. Leaching losses ranged from 11 to 246 kg N/ha. The highest leaching losses occurred when high rates of fertiliser N (300-350 kg N/ha) were applied to the crop at planting when the plants were too small to recover much of the applied N Leaching losses were also greater when the soil mineral N content at the start of the winter was high (e.g. 84 kg mineral N/ha in the 0-60 cm depth of soil compared with 39 kg N/ha). Mineral N contents at the start of winter ranged from 39 to 427 kg N/ha, depending on the previous crop history. The highest value was where compost was regularly used as a soil amendment. There is considerable scope to utilise N more efficiently in winter vegetable production systems by matching N inputs to crop demand and adjusting N inputs to allow for the amount of mineral N present in the soil at planting time.

Not all land under intensive vegetable production is used to grow crops over winter. Uncropped land may be left fallow or planted in a cover crop over winter. Rapidly growing species like triticale and oats can be sown as cover crops over winter. These crops will take up mineral N from the soil, and thus have the potential to reduce nitrate leaching losses. At the Aorangi trial site in the Manawatu, cover crops produced 14-18 t DM/ha between April and September and reduced nitrate leaching in the fallow plots from 38 kg N/ha to 13-20 kg N/ha. Leguminous crops can also be grown over winter to supply N to subsequent crops. At the Leeston trial site in Canterbury, lupins grown over the winter added 60 kg N/ha to the soil.

Additional key words: nitrogen fertiliser, compost, nitrate leaching, cover crops

Introduction

Intensive vegetable production in New Zealand covers an area of approximately 55 500 ha (Kerr *et al.*, 2002). In areas like Pukekohe, Otaki and Oamaru where soil type and climate are favourable, potatoes, spinach, cabbages, broccoli and other green vegetables are grown all year round. Up to three crops per year can be grown, usually with high levels of N inputs.

The winter period is often the most critical for managing N. Leaching losses can be particularly high during winter due to drainage from excess rainfall combined with high nitrate concentrations in the soil from winter fertiliser applications or left over from crops grown during the preceding summer/autumn. Leaching losses of >200 kg N/ha from winter vegetable crops have been recorded in Pukekohe and Levin (Spiers *et al.*, 1996; Williams *et al.*, 2000a; Francis *et al.*, 2002). Such losses represent both an economic loss of N from the farm and an environmental concern when the leached nitrate contaminates surface and ground water. Intensive vegetable production is thought to be the cause of the high nitrate concentrations (>10 µg nitrate-N/ml) recorded in some wells in Pukekohe (Selvarajah, 1999).

The N inputs are particularly high in winter vegetable crops (e.g. >300 kg N/ha; Wood, 1997) to compensate for perceived slower growth rates and plant N uptake. For conventionally grown crops, these N inputs are usually in the form of soluble N fertiliser. Being soluble, this N has a high risk of being leached over winter if not utilised by the crop. For organic farming systems, biological soil processes rather than soluble fertilisers are relied on to provide a source of mineral N to the crop. Thus, organic sources of N are applied to organic crops (e.g. compost and inclusion of legumes in the crop rotation) and the N is released to the crops via mineralisation. In both systems the challenge is to match the N inputs to crop demand to ensure the applied N is used efficiently by the crop, particularly over the winter.

Not all the land under intensive vegetable production is used to grow vegetables over winter. Some of the land may be left fallow or planted in cover crops that are ploughed down in spring. A range of species can be grown as cover crops. For example, when species like cereals and grasses are grown over the winter they can return large quantities of organic matter to the soil. They can also have an important role in managing the N fertility in the soil as they will take up mineral N left in the soil after crops grown in summer/autumn, thus reducing leaching losses (Francis, 1995). When cover crops are ploughed down, the N in the residues is released and can become available to the subsequent crop. Alternatively, growing legumes over winter can add N to the soil for the subsequent crop. This is particularly important in organic vegetable systems where N fixation is an important source of N.

This paper discusses ways of managing N in winter vegetable crops using the results from two field studies. In the first study, N inputs and outputs were measured from typical organic and conventional crops. In the second study a range of cover crops was grown over winter with the aim of determining their potential impact on N fertility. These crops included a range of legumes, cereals and grasses.

Materials and Methods

N inputs and outputs from winter vegetable crops

Inputs and outputs of N were measured at seven sites during winter 2002. Three of the sites were in broccoli crops and four were in potato crops. Also included are data for spinach and cabbage from Williams *et al.* (unpubl. data; 2003). The sites were chosen as being typical for the crops, and background details are given in Table 1. Note that the Pukekohe potato sites were next to each other. At one site the crop was grown with 469 kg N/ha applied as 319 kg N/ha at planting and 150 kg N/ha applied as a side dressing eight weeks later. This is typical of the current fertiliser practice for winter potatoes in Pukekohe. Potatoes at the other site were grown with 259 kg N/ha, applied as 109 kg N/ha at planting and 150 kg N/ha eight weeks later. This rate was used to demonstrate the impact of reducing the amount of N fertiliser applied at planting on crop yield and nitrate leaching. Both sites were managed in the same way and received the same rate of P and K fertiliser (200 kg P/ha and 200 kg K/ha).

Table 1 Location, soil type, planting and harvest dates for the crops used in the N input and output study.

Crop	Location	Soil type	Date planted	Date harvested
Broccoli	Oamaru	Waireka	2 April	7 August
Broccoli	Oamaru	Timaru	29 March	4 August
Organic broccoli	Otaki	Te Horo	6 April	30 July
Cabbage	Pukekohe	Patamahoe	12 May	17 September
Spinach	Pukekohe	Patamahoe	28 May	10 September
Potatoes	Oamaru	Waireka	5 June	2 December
Potatoes	Oamaru	Waireka	3 June	28 November
Potatoes	Pukekohe	Patamahoe	9 May	1 November
Potatoes	Pukekohe	Patamaohe	9 May	1 November

The amounts of fertiliser applied at the conventionally farmed sites, and meal and compost applied at the organic site along with the N content of these inputs were recorded. Soil, herbage and soil solution samples were taken from five replicate plots per site. Plots were 2 m x 1 m and were selected at random throughout the crop. Soil samples were taken to a depth of 60 cm at planting and harvest, and were analysed for KCl extractable nitrate and ammonium (Keeney and Nelson, 1982). The results of these analyses have been combined and are presented as soil "mineral N content" in this paper. Nitrate leaching losses were determined from soil solution nitrate concentrations and drainage estimations (Francis *et al.*, 1994). Soil solutions were obtained from ceramic solution samplers installed 60 cm below the soil surface. Two solution samplers were installed within each replicate per site (10 per site in total). Samples of soil solution were collected after each significant rainfall event (10-20 mm). The amount of drainage was calculated from a water balance based on the measured initial soil moisture, daily rainfall and evapotranspiration (Francis *et al.*, 1994). At harvest, above ground herbage on each plot was harvested by hand, weighed, subsampled and analysed for yield, dry weight and N concentration.

Cover crops

A range of cover crop species was grown in two field trials during 2001. One was on the Aorangi Research Station near Palmerston North. The soil was a Kairanga silt loam and the site had been left fallow for the previous 12 months. Prior to that the site was in pasture. The mineral N content of the 0-15 cm depth of soil was 66 kg N/ha when the trial was established (6 April 2001). The second trial was at Leeston in Canterbury on a certified organic mixed cropping farm. The soil type was a Temuka silt loam and the site had previously been in peas. The mineral N content of the 0-15 cm depth of soil was 45 kg N/ha at trial establishment (11 April).

There were 11 treatments replicated 4 times in a randomised block design, including a fallow where nothing was planted and the weeds were allowed to regrow. Treatments included 'Doubletake' triticale (*Triticosecale* spp.), '4723.4' triticale, 'Hokonui' oat (*Avena sativa* L.), 'Stampede' oat, 'Apollo' Italian ryegrass (*Lolium multiflorum* Lam.), 'Apollo' Italian ryegrass + vetch (*Vicia villosa* Roth), 'Apollo' Italian ryegrass + 'Huia' white clover (*Trifolium repens* L.), yellow sweetclover (*Melilotus officinalis* Pallis), blue lupins (*Lupinus angustifolius* L.) and 'Colenso' red clover (*Trifolium pratense* L.). At the Leeston trial, 'Otama' oats were grown instead of '4723.4' triticale because the latter was not expected to grow well in Canterbury. At both trial sites, the plots were 12 m x 2 m in size.

Nitrate leaching losses in the Aorangi trial were measured using the same technique outlined above. There was insufficient rain in Canterbury to warrant calculating leaching losses (only 283 mm fell over the April-October period in Leeston compared with 438 mm at Aorangi). At the Aorangi site, three ceramic solution samplers were installed per plot at 50 cm depth and samples of the soil solution were collected after each significant rainfall (approximately 20 mm). Due to time constraints, leaching measurements were made in 9 of the 11 treatments (i.e. not in the Doubletake triticale and Hokonui oat treatments).

The Aorangi trial was harvested on 19 September 2001 and the Leeston trial on 3 October. Samples of herbage (45 cm x 50 cm) were cut at ground level from each plot and weighed. Subsamples of the herbage were taken for herbage dissection, dry matter determination and N concentration.

Both trials were managed with no inputs to simulate conditions in an organic system. The weeds were not controlled in any way. Pest and disease incidence was minimal.

Statistical analyses

Data means and standard deviations were calculated for the N input and output trial using Genstat. While the samples were well replicated, the samples were collected from different geographic sites and it was not possible to make statistical comparisons. Data from the cover crop trials were analysed by ANOVA as a randomised block design using Genstat.

Results and Discussion

N inputs

The results of the analysis of N inputs are shown in Table 2. Data from spinach and cabbage crops collected in previous trials in Pukekohe have also been included in Table 3. Details of these trials are given in Williams *et al.* (unpubl. data; and 2003).

Inputs of N varied between crops from 59 kg N/ha in the Oamaru broccoli crops to 469 kg N/ha in the Pukekohe potatoes. The N fertiliser applied to the conventionally grown crops was in the form of a compound N:P:K:S fertiliser (containing typically 12-14% N). The N inputs on the organic crop comprised a mix of compost (20 t/ha @ 60.7 % N on a wet weight basis = 138 kg N/ha), certified fish and bone meal (58 kg N/ha) and certified liquid fish fertiliser (2 kg N/ha).

N losses

The amounts of N removed in harvested green vegetable crops ranged from 20 to 80 kg N/ha according to crop yield. The potato crops removed 37-108 kg N/ha. There were large differences in crop yield and N removed between the potatoes grown in Oamaru and Pukekohe. The Oamaru potato crops are aimed at the high value gourmet market and so are harvested at an earlier stage than the Pukekohe crops.

Leaching losses varied between sites according to drainage, soil mineral N content and the amount of N fertiliser applied. Losses were smallest from the Oamaru broccoli and potato crops (11-25 kg N/ha) where drainage was low (70-111 mm) and soil mineral N content at the planting was also low (39-58 kg N/ha). The other Oamaru sites also had low drainage but the soil mineral N contents were higher (84-177 kg N/ha) and so leaching losses were higher (65-94 kg N/ha). Winter drainage at Pukekohe sites was much greater (373-428 mm) than in Oamaru. In these sites leaching losses were greatest where soil mineral N content was large at planting and/or high N fertiliser rates were applied (e.g. Pukekohe cabbage and spinach). Where soil mineral N levels at planting were low (e.g. Pukekohe potato), leaching losses were increased where high rates of N fertiliser were applied at planting (171 kg N/ha leached from 469 kg fertiliser N/ha compared with 111 kg N/ha leached from 259 kg fertiliser N/ha). Very high leaching losses occurred from crops grown with 400-469 kg N/ha fertiliser because the majority (309-350 kg N/ha) was applied at planting. At this stage the plants were too small to recover significant amounts of N, consequently large amounts of fertiliser N accumulated in the soil leading to large potential leaching losses.

Table 2 Amounts of N applied in inputs, removed in the harvested crop, leached and present in the soil at planting as mineral N.

Measurement	Oamaru		Otaki	Pukekohe		Oamaru			Pukekohe
	Broccoli	Broccoli	Organic broccoli	Cabbage	Spinach	Potatoes	Potatoes	Potatoes	Potatoes
Yield (t/ha)	2.6	2.8	8.1	37	13	16	14	28	26
Soil mineral content	39	84	427	101	204	58	177	41	46
(kg N/ha)	59	59	218	150	400	111	120	469	259
N inputs (kg N/ha)	21	25	38	80	40	32	37	108	103
N removed in crop									
(kg N/ha)	111	94	315	384	428	70	82	373	373
Drainage (mm)	11	91	180	178	246	25	65	171	111
Nitrate leached									
(kg N/ha)									

In the organic crop, all of the N applied was in organic forms so it was not readily leached. Thus, we may have expected leaching losses to be less than in conventionally grown crops. However, the soil test at the start of the trial shows that a large amount of mineral N (427 kg N/ha) had accumulated in the soil, presumably mineralised from previous organic N inputs. The amount of mineral N in the soil was considerably more than the N requirement of the broccoli crop and so leaching losses occurred with the high drainage measured at this site (315 mm).

The balance of N inputs and outputs shown in Table 2 suggest that inputs greatly exceed outputs at most sites. Consequently N is not being efficiently cycled. Improvements could be made through better consideration of the amounts of N applied in fertilisers and composts, and recycled via crop residues.

Managing N fertiliser

It is possible to reduce the amount of N fertiliser applied and reduce leaching losses while still achieving high yields by improving the utilisation of the fertiliser by the crop. In particular, care should be taken with the amount of N applied at planting. While vegetable crops appear to need some N for establishment, applying more N than can be taken up by the small plants is inefficient. Comparing the data for the two Pukekohe potato sites shows that reducing the amount of N applied at planting by 200 kg N/ha had little effect on yield, but reduced the amount of N leached by 60 kg N/ha. Similar results have been obtained in potatoes (Martin *et al.*, 2001; Williams *et al.*, 2000a) and spinach (Williams *et al.*, 2003).

Crop residues

For green vegetable crops, only approximately 50% of the above ground crop is removed with the outer leaves and stems left behind on the soil surface. Vegetable crop residues have a relatively low C:N ratio (e.g. 14:1-19:1) and so can mineralise rapidly upon incorporation (e.g. within one month; Berry *et al.*, 2002). Assuming a harvest index of 50% for vegetable crops, the data in Table 2 suggest approximately 21-25 kg N/ha could become available to the subsequent crop from decomposing crop residues. This could provide a significant proportion of the N required by the subsequent vegetable crop.

Compost

The compost used on the organic broccoli crop added 138 kg N/ha. The C:N ratio was 57:1, suggesting that it would be relatively slow to decompose and the main contribution of the compost is to the soil organic N pool (Berry *et al.*, 2002). However, the soil mineral N content at the organic site when the crop was planted, was very high, suggesting that mineralisation of organic N was readily occurring. This N may have come from previous compost applications, residues from the previous crop or even the previous green manure crop.

Cover crops

The cereals established rapidly following planting in the autumn, and large amounts of dry matter (14-18 t DM/ha) were produced by the triticale and oat cover crops in the Aorangi cover crop trial (Table 3). Smaller amounts were produced by the ryegrass alone or in mixtures (8-10 t DM/ha). The lupins established poorly and accounted for only 18% of the total dry matter. Similarly the clovers established poorly as they were probably sown too late in the autumn. Clovers accounted for <1% of the dry matter production in the clover treatments. The cereal and ryegrass treatments had a significant impact on reducing nitrate leaching with losses of 13-20 kg N/ha compared with 38-51 kg N/ha leached from the fallow and legume plots.

Table 3 Yield of grass/cereal, weed, legume and amount of nitrate leached from winter cover crops at Aorangi, Manawatu.

Cover crop	Sowing rate (kg/ha)	Grass/cereal yield (t DM/ha)	Weed yield (t DM/ha)	Legume yield (t DM/ha)	Total yield (t DM/ha)	Amount of nitrate leached (kg N/ha)
Doubletake triticale	140	17.8	0	0	17.8	NM
4723.4 triticale	140	15.3	0	0	15.3	13.3
Hokonui oat	110	14.3	0	0	14.3	NM
Stampede oat	110	13.7	0	0	13.7	20.5
Apollo Italian Ryegrass	25	8.3	0	0	8.3	28.9
Apollo+vetch	15+3	8.7	1.0	0.2	9.9	17.6
Apollo + white clover	15+3	11	0	0	11.0	18.8
Yellow sweet clover	3	0	4.8	0	4.8	32.5
Blue lupin	190	0	4.7	1.0	5.7	41.1
Red clover	5	0	3.5	0.2	3.7	50.5
Fallow		0	5.0	0	5.0	37.6
$LSD_{5\%}$		2.84	1.79	0.36	3.37	14.9

NM = not measured

Dry matter yields in the Leeston trial were lower than in Aorangi (Table 4). The triticale, oat and ryegrass all produced 4.1-7.0 t DM/ha and these yields were significantly higher than those from the fallow plots by about 2 t DM/ha. As at Aorangi, the clovers did not establish well although the vetch and lupins grew well. The lupins grew particularly well, accounting for 57% of the 5.6 t DM/ha produced. The vetch accounted for 16% of the total DM production. The triticale had the highest N uptake

although it was not statistically higher than the oat N uptake. Lupins also had a high N uptake, presumably due to fixation of N rather than uptake of soil mineral N. It was estimated that the lupins fixed 60 kg N/ha and the vetch fixed 40 kg N/ha. The other legumes did not produce enough DM to warrant estimating N fixation.
Measurements of dry matter production, N uptake and nitrate leaching were made from cover crops grown on the Otaki organic property (unpublished data). The results showed that an oat crop grown between May and October produced 5 t DM/ha, recovered 80 kg N/ha and resulted in a leaching loss of 27 kg N/ha. The leaching loss can be compared with the 180 kg N/ha leached from the adjacent broccoli crop (Table 2).

Table 4 Yield of grass/cereal, weed, legume and nitrogen uptake in winter grown cover crops at Leeston, Canterbury.

Cover crop	Sowing rate (kg /ha)	Grass/cereal yield (t DM/ha)	Weed yield (t DM/ha)	Legume yield (t DM/ha)	Total yield (t DM/ha)	N uptake (kgN/ha)
Doubletake triticale	140	6.6	0.2	0	6.8	155
Otama oat	110	4.3	0.6	0	4.9	142
Hokonui oat	110	3.2	0.9	0	4.1	98
Stampede oat	110	5.5	0.9	0	6.4	119
Apollo Italian ryegrass	25	5.5	0.7	0	6.2	96
Apollo+vetch	15+3	5.1	0.2	1.0	6.3	147
Apollo+white clover	15+3	6.5	0.4	0	7.0	120
Yellow sweetclover	3	0	0.2	0	2.3	51
Blue lupins	190	0	2.4	3.2	5.6	146
Red clover	5	0	1.7	0.2	1.9	48
Fallow		0	2.2	0	2.2	96
$LSD_{5\%}$		1.07	0.73	0.14	1.23	44.3

Conclusions

Results from these studies and others (Francis *et al.*, 2002; Williams *et al.*, 2000a; unpubl. data; 2003) show that leaching losses can be very high from both conventional and organic winter vegetable crops (>150 kg N/ha). Leaching is highest when levels of soil mineral N are high, when winter vegetable crops are planted and when rates of N fertiliser applied at planting exceed the immediate needs of the crop plants. More efficient utilisation of N over winter can be achieved by:

- matching N inputs to crop uptake by reducing the amount of soluble N applied at planting and applying strategic side dressings,
- measuring the soil mineral N content at planting to identify the background level and adjust N inputs accordingly. Currently routine soil tests do not include mineral N analyses, but there are significant benefits in carrying out these analyses,
- taking account of the N content of composts and crop residues when determining N inputs for a crop,
- sowing rapidly growing cover crops like triticale or oats in the autumn instead of leaving the land fallow over winter or growing winter vegetable crops. These cover crops can scavenge N from the soil and have the potential to reduce nitrate leaching.

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Effect of fertiliser rate and type on the yield and nitrogen balance of a Pukekohe potato crop

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Abstract

The possibility of reducing the financial and environmental costs of fertiliser application to potatoes (*Solanum tuberosum* L.) by reducing the rate of application of nitrogen (N) fertiliser, and by using slow release or foliar fertilisers to make the fertiliser N more slowly available to the crop but without impacting on yield, was investigated. An experiment at Pukekohe in the winter of 2000 examined the effect of rate and form of N fertiliser on the growth, yield and N balance of a potato crop. The fertilisers used were ammonium sulphate nitrate (ASN) at 242, 350 and 472 kg N/ha, ASN coated with the N-release inhibitor dimethylpyrazole phosphate (DMPP) at 242 and 350 kg N/ha, and the foliar fertiliser Supa N 32 (four applications of 4 kg N/ha as Supa N 32 over 336 kg N/ha applied as ASN). There was no significant increase ($P<0.05$) in tuber yield with N applications over 242 kg/ha, and form of N had no significant effect ($P<0.05$) on tuber yield. Petiole nitrate levels in fertilised treatments were generally over 20,000 mg/kg, excessive according to USA guidelines, so N was not limiting yield. N leaching losses were 82 kg/ha without any N fertiliser application. Leaching under ASN was 167 to 208 kg N/ha. Increasing the ASN rate over 242 kg N/ha resulted in an accumulation of over 200 kg mineral N/ha as nitrate in the soil profile when the crop was harvested. Coating with an N inhibitor reduced leaching by around 30%, but also led to an accumulation of over 250 kg mineral N/ha as ammonium in the soil profile when the crop was harvested. Applying some fertiliser as a foliar spray had no significant effect on leaching or mineral N accumulation. A green manure oat crop, planted after the potato crop was harvested in October, was sampled for yield and N content in January 2001. The oat crop took up 52 kg N/ha in the control plots, and 87 to 133 kg N/ha from the N fertiliser plots, with significantly more being taken up by the ex DMPP plots at equivalent fertiliser rates. This entire N was mulched back into the soil as organic N.

Additional key words: *nitrogen inhibitor, foliar fertiliser, slow release fertiliser, leaching, oats, green manure, petiole nitrate.*

Introduction

Current fertiliser practice for winter grown potatoes in New Zealand is to apply up to 500 kg fertiliser nitrogen (N), on the basis that any deficiency reduces yield. However, research results both in New Zealand (e.g., Martin, 1995b) and overseas (Rourke, 1985) indicate that much of this fertiliser is not taken up by the crop, and could well leach into groundwater either during the growth of the crop or after the crop is harvested. Overseas research has shown that leachable fertiliser levels are higher under potatoes than many other crops (Sylvester-Bradley and Chambers, 1992), and a New Zealand study predicted that winter-grown potato crops in the Pukekohe area are likely to have the greatest impact on groundwater nitrate of any vegetable crop (Crush *et al.*, 1997). Vegetable production has already been identified as a major contributor to the high concentration of nitrate measured in groundwater in the Pukekohe area (Selvarajah, 1999). Regional councils are becoming increasingly concerned about groundwater quality and may place restrictions on applications of fertiliser at levels they consider excessive. Research and farmer trials overseas indicate that applying foliar fertilisers and coating conventional fertilisers with release inhibitors have increased potato yields and tuber size by up to 25% compared to current practice (e.g., Anonymous, 1998). This indicates that there may be opportunities for New Zealand potato growers to use slow release or foliar fertilisers to both increase yields and reduce potential for groundwater pollution.

The objective of this research was to investigate the possibility of reducing the financial and environmental costs of fertiliser application to winter grown potatoes by more closely matching the supply of fertiliser N with crop demand for N by using:

- Reduced rates of conventional fertiliser compared to farmers' practice;
- Conventional fertiliser coated with a release inhibitor to make the fertiliser N more slowly available to the crop; or
- Foliar applications of a liquid fertiliser to ensure rapid uptake of N by the crop.

A trial was undertaken to compare these approaches on a winter potato crop at Pukekohe, planted in May 2000.

Materials and Methods

The trial was carried out on a southwest facing site (5° slope) on Pukekohe Hill. The soil type was a mixture of Patamahoe and Whatitiri clay loams, which are deep granular soils derived from volcanic ash. The site had a long history of intensive vegetable production, and in recent years had been double cropped with winter potatoes and summer green feed crops that were mulched back into the soil. Soil fertility information at planting for the 0-15 cm depth indicated low to very low levels of carbon (2% organic C) and N (19 kg mineralisable N/ha), but high to very high levels of P, K, and Mg (quick test values of 159, 30 and 25 respectively), and a pH of 5.7. These analyses are typical of Patamahoe and Whatitiri soils used for long-term intensive vegetable production.

The trial had seven fertiliser treatments, detailed in Table 1. They included a zero-N fertiliser control and the standard grower practice of 300 kg N/ha applied at planting, followed by 172 kg N/ha when the plants had emerged (subsequently referred to as F472). The F350 and F242 treatments had a lower total N application rate, with the timing of the post-emergence applications altered to more closely match crop demand. N-fertiliser in the F472, F350 and F242 treatments was applied as ammonium sulphate nitrate (ASN: 26% N, 14% S).

Treatments I350 and I242 were the same as F350 and F242, but the ASN was treated with the N-inhibitor dimethylpyrazole phosphate (DMPP). DMPP is an ammonium stabiliser and so holds the fertiliser N in the ammonium form for longer before allowing it to convert to nitrate. This inhibitor is manufactured by the Compo Division of BASF in Germany and is marketed under the trade name Entec. There was 1% DMPP in the treated ASN.

Table 1. Rate (kg N/ha) and timing of N fertiliser applications. F = N fertiliser (ASN[1]), I = inibitor (DMPP[2]) coated ASN fertiliser, S = N fertiliser applied as solid (ASN) and foliar (Supa N 32[3]).

	Application date							
Treatment	2 May	14 Jun	19 Jun	9 Jul	10 Jul	31 Jul	3 Aug	20 Aug
Control	0	0	0	0	0	0	0	0
F472	300	172	0	0	0	0	0	0
F350	180	57	0	0	57	0	57	0
F242	150	46	0	0	46	0	0	0
I350	180	57	0	0	57	0	57	0
I242	150	46	0	0	46	0	0	0
S350 -solid	180	52	0	0	52	0	52	0
-liquid	0	0	4	4	0	4	0	4

[1] ammonium sulphate nitrate: 26% N, 14% S
[2] dimethylpyrazole phosphate
[3] 50/50 mixture of urea and ammonium nitrate

The remaining treatment (S350) included four applications of a liquid foliar fertiliser (Supa N32), with the ASN fertiliser application rate reduced to keep the total N application to 350 kg/ha. Supa N32 contains 32% N as a 50/50 mixture of urea and ammonium nitrate. The fertiliser was applied as a 10% solution using a hand held boom.

The fertiliser treatments were replicated four times and arranged in a randomised block design. Each plot was 20 m long and 6 plant rows wide. The rows were 81 cm apart and tubers (cv. Ilam Hardy) were planted 20 cm apart, giving a planned 600 plants/plot. The trial was planted on 2 May and harvested on 16 October.

All plots received a base fertiliser application of 200 kg P/ha, 175 kg K/ha, 67 kg Mg/ha and 60 kg S/ha (applied as a blend of superphosphate, triple superphosphate, potassium chloride and calcined magnesite). All fertiliser applied at planting (base and N fertiliser) was applied by hand to the furrows immediately after planting and before the soil was mechanically moulded. All post-emergence solid fertiliser was broadcast by hand evenly over ridges.

Measurements of crop N uptake were made on 14 June, 10 July, 3 August, 3 September and 16 October. At each sampling time 20 plants from each plot were hand harvested from a 2 m length of two adjacent rows. The plant foliage, roots and tubers were separated, washed, dried, weighed and analysed for N content on a LECO CNS-2000 analyser. At the final harvest the tubers were also graded for their marketability before being weighed.

Ten leaf petioles per plot were collected using the standard technique, outlined by Martin (1995a), on 19 June, 3 July, 17 July, 31 July, 14 August, 27 August and 11 September, and analysed for nitrate N at ARL Laboratories, Napier.

Two soil samples were collected from each plot to a depth of 60 cm immediately before planting and immediately after harvest. The samples were dried, extracted with 2M KCl, and the resulting solution measured for nitrate and ammonium N on an RFA-300 Continuous Flow Analyser.

On 1 May and at harvest the soil in each plot was sampled to a depth of 15 cm by taking 6 cores per plot with a standard soil corer. In addition, the 15-30 cm and 30-60 cm layers were sampled in each plot by digging 2 holes per plot to a 60 cm depth and sampling down the sides of the hole. The samples were dried, extracted with 2M KCl, and the resulting solution measured for nitrate and ammonium N on a RFA-300 Continuous Flow Analyser.

Nitrate leaching losses were determined from nitrate concentrations in the soil solution and from drainage calculations (Francis *et al.*, 1992). Soil solutions were obtained from ceramic solution samplers installed at 60 cm depth. Four samplers were installed in each plot immediately after planting. Care was taken to install the samplers halfway down the ridges. Solution samples were taken after each significant rainfall event (>20 mm), and were analysed for nitrate N on an RFA-300 Continuous Flow Analyser. The amount of drainage was calculated from a water balance based on measured initial soil moisture, daily rainfall and evapotranspiration (Francis *et al.*, 1992). These meteorological data were obtained from the NIWA climate database (Station C74283 2006 Pukekohe EDR). Visual estimates of the proportion of the soil surface covered by the crop leaves were used to account for differences in evapotranspiration between the treatments using the method of Francis *et al.* (1992).

The trial area was subsequently planted with an oat green manure crop. A line of black oats was drilled at 100 kg/ha in 15 cm rows in late November, and was mulched in the first week of February. No fertiliser was applied to the crop. Immediately prior to mulching, the plots were scored for height and density. For yield estimates, two or three 0.3 m^2 samples were cut to ground level in five randomly selected plots and oven-dried. The dry weights were calibrated against the visual height and density scores to calculate the dry matter yields in the other plots. For N contents, 20-30 tillers taken at random from each plot were couriered to Lincoln, then dried at 60°C, ground and analysed for N using a LECO CNS-2000 analyser.

Results

Weather and drainage

The rainfall (598 mm) at Pukekohe Research Station (5 km from the trial site) in the winter of 2000 was close to the long term average of 616 mm, although June, July and August were around 12 mm wetter than average, and May and September around 25 mm drier.

Mean temperatures were over 1°C higher than average from May to July, but around 0.9°C cooler in August and September. There were a number of significant rainfall events, and the calculated cumulative drainage was around 400 mm more than used by the crop for growth (Fig. 1).

Tuber yield

About 85% of the crop had emerged by the end of May, and tubers were initiated during late June/early July. All tops had completely died down by the final harvest on 16 October. Applying N fertiliser increased yield over the control, but rates and form of N fertiliser higher than 242 kg N/ha had no effect significant effect on yield. The control treatment yielded significantly less than the N treatments due to the combined effect of a smaller total weight of tubers and a smaller proportion of marketable tubers (those over 40 g or not grossly deformed) (Table 2). However, tubers in this treatment had higher dry matter content than treatments receiving N fertiliser, except treatment I242. There was no difference among N treatments in yield, marketable yield or dry matter content of tubers.

Figure 1. Rainfall events (Pukekohe Research Station) and cumulative drainage calculated using the method of Francis *et al.* (1992).

Table 2. Mean final harvest tuber yields and dry matter (16 October harvest) and mean maximum total crop N uptake (4 September harvest).

Treatment	Tuber yield (t/ha)	% market[1] tubers	Market yield (t/ha)	Non-market yield (t/ha)	Tuber DM (%)	Crop N uptake (kg/ha)
Control	12.73	56.30	7.24	5.49	19.44	37.5
F472	29.95	83.20	24.98	4.98	17.98	129.6
F350	29.69	80.40	23.91	5.79	18.02	124.1
F242	28.49	83.80	24.15	4.35	17.98	123.4
I350	25.81	81.30	21.00	4.82	18.15	107.1
I242	28.33	81.40	23.04	5.29	18.63	101.3
S350	27.75	81.90	22.75	5.00	18.32	117.0
LSD $_{(P<0.05)}$ (df=18)	4.756	9.99	5.29	1.96	0.92	17.9

[1] tubers over 40 g and not grossly deformed

Petiole N levels

Compared to the guidelines for petiole analysis published in the USA (Kleinkopf *et al.*, 1984), only the control treatment from July onwards had N values that were considered inadequate to deficient (Fig. 2). All the other treatments had levels that the guidelines classify as excessive, although the I242 treatment was approaching optimum guideline levels by September. The inhibited release fertiliser produced plants with significantly lower petiole nitrate levels than those receiving equivalent rates of ASN throughout the trial.

Crop N uptake

Maximum N uptake in the fertiliser treatments occurred at the 4 September sampling. At the 242 and 350 kg N/ha rates, the contrast between ASN (124 kg N/ha) and DMPP (104 kg N/ha) was significant (P<0.05), but there was no significant difference among ASN and foliar applications. The control treatment had a considerably lower N uptake throughout, reaching 35 kg N/ha at the 4 September sampling.

Soil N at planting and harvest

At planting there was 51 kg/ha of mineral N in the soil (Table 3), about one-third of which was in the top 30 cm and two-thirds in the 30-60 cm layer. Over 90% of this mineral N was present as nitrate.

At harvest there were large differences in soil N between treatments. Total N levels in the 0-60 cm zone in the control treatment at harvest were half those at planting. In all other treatments, 0 – 60 cm soil N levels were increased, from 2.5 times to over 8 times the level at planting. Increasing ASN application increased 0 – 60 cm soil N at harvest, although the difference between the 350 and 472 kg N/ha rates were not significant (P<0.05). At the 242 And 350 kg N/ha rates, DMPP treatments had significantly higher total N than ASN treatments, but the foliar N application was not significantly different to the F350 treatment.

In the ASN and ASN plus foliar treatments the increase in soil N from planting to harvest was mainly in nitrate N (85% of the total). The nitrate accumulated at all depths with very large amounts accumulating in the 30-60 cm layer under the F472 and F350 treatments. In contrast, ammonium was the dominant form of N in the inhibited treatments (79%) and accumulated mainly in the 0-15 cm depth. Note that under these treatments some nitrate accumulated further down the profile although the amounts were less than under the uninhibited fertiliser treatments.

Applying some N as foliar fertiliser had no effect on soil ammonium or nitrate levels as the soil mineral N content in the S350 split treatment was similar to the F350 treatment.

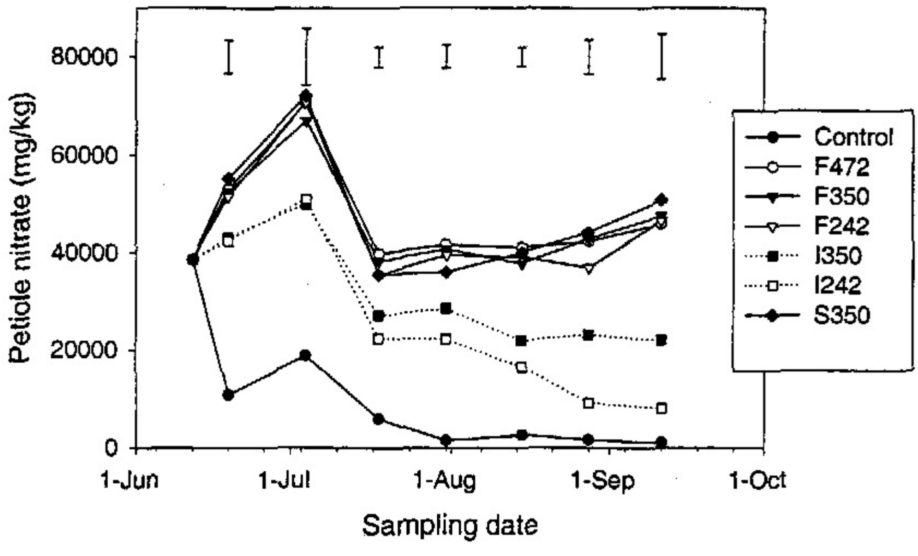

Figure 2. Mean petiole nitrate levels in the seven fertiliser treatments. Treatment details are in Table 1. Vertical bars are LSD 5% (df=18) obtained from ANOVA for each date separately.

Table 3. Mean soil ammonium, nitrate and total N (kg/ha) at planting (averaged across treatments) and at harvest for three sampling depths.

	0-15 cm		15-30cm		30-60 cm		0-60 cm		
Treatment	NH_4	NO_3	NH_4	NO_3	NH_4	NO_3	NH_4	NO_3	Total
At planting	0.7	3.9	1.2	12.4	1.4	30.8	3.3	47.1	50.5
At harvest									
Control	3.7	7.5	0.1	5.3	0.2	9.5	4.0	22.3	26.0
F472	36.3	75.7	0.6	47.1	0.0	129.0	37.0	251.8	289.0
F350	28.1	71.4	0.4	51.6	0.0	92.6	28.5	215.6	244.0
F242	27.4	47.3	0.8	19.2	0.1	40.5	28.3	107.0	135.0
I350	323.8	16.7	23.5	43.3	0.1	40.3	352.4	100.3	443.0
I242	262.1	15.4	17.3	30.8	0.9	28.2	280.2	74.4	355.0
S350	35.9	78.7	1.1	43.9	0.0	115.6	37.0	238.2	275.0
$LSD_{(P<0.05)}$ df=18	40.56	23.21	18.24	21.61	0.877	49.27	49.14	75.0	93.5

Soil N leachate

The cumulative amounts of N leached during the winter are shown in Figure 3. Leaching losses began within a month of planting with quite large losses occurring during the heavy rain periods that occurred in early June and again in early July (Fig. 1). Approximately half of the total amount of N leached was lost during the first two months of the trial.

The amount of N leached from the control plots (no N fertiliser) was 82 kg N/ha (Fig. 3). Application of fertiliser N more than doubled the amount of N leached with 208-219 kg N/ha leached from the F350 and F472 treatments. At the final sampling on 3 October, leaching losses from the inhibited treatments were 131 kg N/ha, 63 kg N/ha lower (significant at P<0.05) than from equivalent uninhibited rates. The same paired

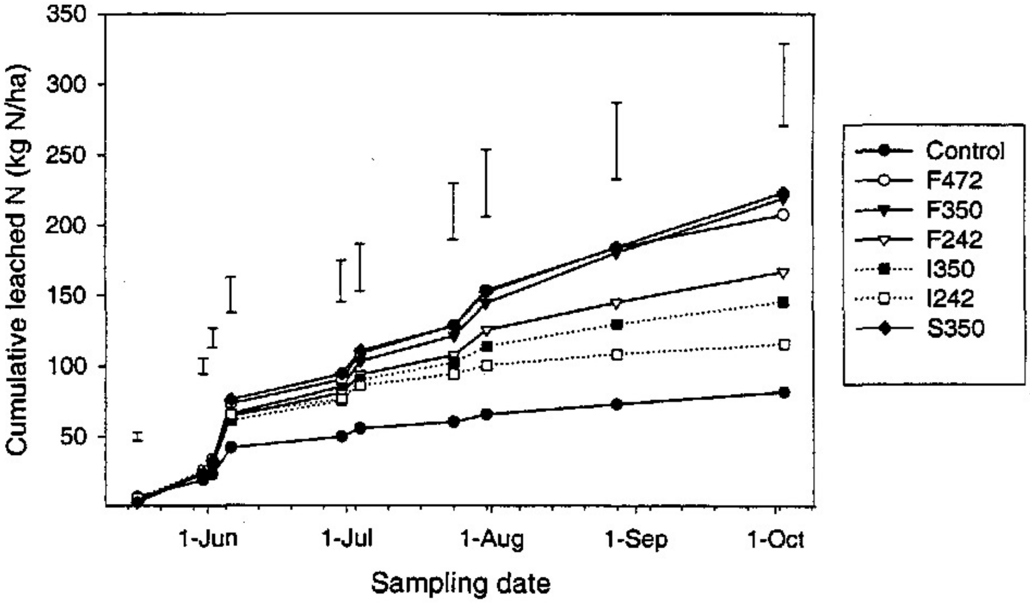

Figure 3. Mean cumulative leachate N levels under the seven fertiliser treatments. Treatment details are in Table 1. Vertical bars are LSD 5% (df = 18) obtained from ANOVA for each date separately.

contrast at the late August sampling was also significant ($P<0.05$) showing that the DMPP N inhibitor can reduce nitrate leaching. There was no significant difference between ASN and ASN plus foliar treatments in the amount of N leached over the winter, indicating that applying some of the N as a foliar spray did not reduce leaching.

Oat yield and N uptake (excluding roots)

Depending on the previous fertiliser treatment, the greenfeed oats produced 3030-4550 kg above ground dry matter/ha during the 10 weeks they were grown (Table 4). Significant quantities of root material would have also been produced, but these were not measured in this study. Oat yields may have been affected by a severe outbreak of rust on the crop. Despite this there were differences in oat yield, N content and N uptake among the treatments. These differences reflected the mineral N content of the soil when the potatoes were harvested. Oat yield and N concentration were significantly lower in the control than in other treatments, and were significantly lower in the F242 treatment than the other fertilised treatments.

Table 4. Mean oat dry matter yield, % N in dry matter and N yield.

Treatment	Yield (DM (kg/ha))	% N in DM	N yield (kg/ha)
Control	3030	1.71	52
F472	4380	2.88	126
F350	4360	2.66	116
F242	3800	2.28	87
I350	4600	2.89	133
I242	4350	2.50	109
S350	4550	2.63	120
LSD $_{(P<0.05)}$ df=18	510	0.208	16.7

N balance

Table 5 summarises the amounts of N leached from the potato crop and recovered by the potatoes, and the change in soil mineral N between planting and harvest of the potatoes. Their sum shows that more N was measured in the leachate, soil and plants than was applied in the fertiliser.

No attempt was made to measure mineralisation of soil organic N during this trial. The N balance for the control treatment suggests that at least 92 kg N/ha was mineralised, indicating that mineralisation is a significant process in these soils.

Discussion

The winter grown potato crop in this trial yielded approximately 30 t tubers/ha. This is a relatively low yield compared with crops sown later in the winter or in spring. Consequently the crop only took up a maximum of 130 kg N/ha. This was less than the lowest rate of N fertiliser applied to the crop and considerably less than the approximately 250 kg N/ha found in another potato crop at Pukekohe (Williams *et al.*, 2000) and the approximately 300 kg N/ha in crops at Lincoln (Martin, 1995b; Martin *et al.*, 2001). However, petiole N levels were very high, and %N in the tops and tubers was higher than at trials at Lincoln (Martin, unpublished data), suggesting that the low yields were not due to poor N uptake. This crop was

Table 5. N fertiliser applied, N fertiliser lost to leaching and to the plant, difference between initial and final soil test N, and amount of extra N in the soil at the final potato harvest not accounted for (all in kg/ha).

Fertiliser treatment	N fertiliser applied (a)	N leached (b)	Maximum plant N uptake (c)	Measured change in soil mineral N (d)	Extra N in soil at final harvest (b+c+d-a)
Control	0	82	38	-25	95
F472	472	208	130	238	104
F350	350	219	124	193	186
F242	242	167	123	84	132
I350	350	146	107	392	295
I242	242	116	101	304	279
S350	350	224	117	224	215

planted and harvested earlier than the crop of Williams *et al.* (2000), and lower soil and air temperatures were probably the major constraint to growth.

This raises the question: "how much N fertiliser should be applied to May sown potato crops?" The results from this trial show that the current practice of applying more N fertiliser than to later sown crops to compensate for lower soil temperatures is inefficient. In fact, as crop yield was lower, less fertiliser was needed rather than more. The crop took up 100 kg N/ha or less, and so the additional N remained in the soil where it is subject to leaching. Furthermore, mineralisation of soil organic N appears to make some contribution to the N supply, further reducing the reliance on N fertiliser. The yield from the control plots clearly showed that the potato crop required some N fertiliser but there was no yield advantage in applying more than 242 kg N/ha. Even this rate appears to be too high, as there were still significant quantities of mineral N remaining in the soil at harvest, and leaching losses were double the amount leached from the control. In this trial (and others, e.g., Williams *et al.*, 2000) we have yet to establish the minimum rate of N required by winter grown potato crops in the Pukekohe region.

The inhibited fertiliser treatment showed potential for potatoes in Pukekohe, with less N leached during the growth of the potato crop. Less N was also taken up by the crop, but this did not affect yield. The very large amount of soil mineral N remaining at harvest suggests that the N application rates were too high. This residual N may be taken up by a subsequent crop as ammonium N or, more likely, once nitrification is complete, as nitrate, which is more readily taken up by plants or leached. Significantly more N was taken up by the subsequent oat crop from the plots that had received inhibited fertiliser (Table 4), but this was small in relation to the amount of N left in the soil after the potatoes (Table 5). So there was a considerable amount of mineral N left for the following winter crop or for leaching into the groundwater.

The ideal slow release fertiliser formulation would make the N available over the four months of the crop. Formulations designed to vary the rate of release of fertiliser N are available overseas (Dan Drost, pers. comm.). It would be useful to test such formulations in the Pukekohe environment to identify those best suited to the range of crops and leaching conditions there.

However, relying on a slow release fertiliser to be effective in a situation where N rates are much higher than required by the crop is risky. A more sensible approach would be to appeal to farmers to reduce N applications to their crops, possibly in combination with applying N at different times (Williams *et al.*, 2000). Data from this trial and others show the importance of minimising nitrate leaching during the first two months after planting and before the crop is established. Further work is required to evaluate slow release fertiliser at lower rates than used in this trial. An economic evaluation of the cost:benefit ratio of these products is also required.

The inhibitor used in this trial inhibits the conversion of ammonium to nitrate. This would include ammonium produced by mineralisation of soil organic N. This indicates that mineralisation may have resulted in the release of around 280-300 kg N/ha, the amount of N unaccounted for in Table 5). In the other treatments this ammonium may have been converted to nitrate and lost through denitrification, another process not measured in this experiment but thought to occur at high rates in soils where very high N fertiliser rates are used, e.g. in vegetable production systems (Ryden and Lund, 1980). It appears that only part of this mineralised N became available in time for the growing crop, as only 92 kg/ha was accounted for in the control treatment.

The foliar fertiliser had an effect on the crop similar to the split applications of solid fertiliser. Given that only low N rates can be applied as a foliar spray without burning the leaves, the benefit from such fertilisers is only likely to occur when the crop is becoming deficient in N. In this trial, the treatment that included the foliar fertiliser yielded no better than treatments receiving 100 kg less N/ha. As with slow release fertilisers, foliar fertilisers are unlikely to improve crop performance when the crop already contains very high levels of N. Any future work with foliar fertilisers should be carried out under more marginal N supply conditions.

Residual nitrate N left in the soil at harvest can be leached out of the soil if it is left fallow. A better option is to grow a cover crop like greenfeed oats, which is a good N scavenger (Francis and Williams, 1997). In this study the oat cover crop recovered 87-133 kg N/ha from the soil in the fertiliser treatments – a significant amount of N that may have otherwise been lost. It also provided up to 4500 kg above ground DM/ha and an unmeasured amount of below ground DM, providing a valuable contribution of organic matter to the soil. The entire N taken up by the oat crop was mulched into the soil. This N has the potential to become available to the subsequent crop, but its actual availability and the pattern of availability are unknown.

This trial has raised some questions about the suitability of current soil N tests on soils derived from volcanic ash. The current oat crop was mulched in, and so the 133 kg N/ha was returned to the soil. As the previous cropping history was of high N application rates to winter potatoes followed by mulched in green manure crops, presumably with roughly similar N levels, then why were the N levels so low at the start of the experiment? Conversely why were soil N levels at harvest much higher than expected from the other components of the soil N balance? Very low initial soil N levels have been found in other trials at Pukekohe (C Tregurtha, pers. comm.), suggesting that the soil tests currently used do not accurately reflect the soil N available to the plant or at risk of leaching.

Conclusions

The rates of N fertiliser currently applied by the farmer at this site in this season could have been more than halved without affecting crop yield. Rates and forms of fertiliser, which differed from the minimum application rate of 242 kg N/ha, had no effect on yield or crop N uptake.

N uptake and crop yields were low in this trial, but petiole and plant N analyses indicated high levels of N in the plant, so N was not limiting yield in fertilised treatments.

N leaching losses were high even without any N fertiliser application, but were increased by 250% by the ASN and ASN plus foliar treatments. Inhibited fertiliser treatments reduced leaching by 33% compared to ASN fertiliser.

All N fertiliser applications increased the level of mineral N in the soil at harvest, especially in the inhibited fertiliser treatments. For the control and ASN fertiliser treatments, around 80% of the N were in the nitrate form, whereas after applications of inhibited fertiliser 79% were in the ammonium form.

The subsequent oat crop took up 52 kg N/ha in the control plots, but up to 133 kg N/ha from the N fertiliser plots, with significantly more being taken up by the inhibited plots. This entire N was mulched back into the soil as organic N.

This study raises some questions about the best type of soil test for predicting plant available and leachable N on this soil type.

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Reading 3.3.3

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Winter nitrate leaching losses from three land uses in the Pukekohe area of New Zealand

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Abstract The effects of three different land uses (dairy grazing, winter potatoes, and winter greens [spinach, cauliflower or cabbage] production) on soil mineral N contents and nitrate leaching losses from late June to early October 2000 were investigated on 18 commercial paddocks. All paddocks were in the Pukekohe area (approximately 50 km south of Auckland) on Patumahoe clay loam soils and received typical management practices for the district. On average, dairy paddocks received the least amount of N fertiliser during the study period (84 kg N ha^{-1}), had the lowest soil mineral N content in June (32 kg N ha^{-1}) and had the lowest leaching loss (15 kg N ha^{-1}). On average, potato paddocks received the greatest amount of N fertiliser (481 kg N ha^{-1}), had the greatest soil mineral N content in June (184 kg N ha^{-1}) and had the greatest leaching loss (114 kg N ha^{-1}). The winter greens paddocks were intermediate between the other land uses. Leaching losses from the potato and greens paddocks were the result of large applications of fertiliser N before winter and the rapid mineralisation of residues from the previous greens crops.

Keywords nitrate leaching; dairying; potato; green vegetables; groundwater; fertiliser

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INTRODUCTION

Elevated nitrate concentrations have been measured in shallow groundwater and surface water in many areas of New Zealand (Bright et al. 1998; Francis et al. 1999). In most cases, non-point sources in intensive agricultural production systems are regarded as the main contributor to this contamination (Selvarajah et al. 1994; Cathcart 1996). However, the land use that contributes most to this contamination may vary between regions. For example, contamination of groundwater and surface water in New Zealand is perceived to be a serious consequence of dairy farming in some regions (de Klein & Ledgard 2001) and of winter vegetable production in other regions (Anon. 1997; Crush et al. 1997). Similar concerns have been reported overseas for both dairy production (e.g., Jarvis 2000) and vegetable crops (e.g., MacDonald et al. 1997; Waddell et al. 2000).

Leaching losses under dairying arise from high rates of N cycling in grazed pastures, with the size of the potential leaching loss increasing with the stocking rate (Jarvis 2000). Most of the nitrate that is leached from dairy pastures comes from urine patch areas, which have very high concentrations of N that are greatly in excess of immediate plant requirements (Haynes & Williams 1993; Ledgard et al. 1999). In contrast, nitrate that is leached from winter vegetable crops largely originates from either applied N fertiliser or from the breakdown of postharvest crop residues. High rates of N fertiliser are often applied to these crops in an attempt to overcome their slow growth rates and their sparse root systems (Goulding 2000). Yields are often increased by these high fertiliser rates, although fertiliser recovery rates are often low, leaving large amounts of N in the soil that are susceptible to leaching (Greenwood et al. 1989; Rahn et al. 1992). The return of large amounts of postharvest plant residues also contributes to the high leaching loss potential under vegetable cropping. The returned residues usually have low C:N ratios and mineralise rapidly when incorporated, resulting in the accumulation of large amounts of nitrate in the soil (De Neve & Hofman 1998; Rahn et al. 1998; Mitchell et al. 2001).

Measurements of nitrate leaching losses have previously been reported for a number of different land uses in New Zealand (Painter et al. 1997). Research has also investigated ways of reducing nitrate leaching losses from particular land uses (e.g., Francis 1995; Williams et al. 2000a). However, as leaching losses can vary greatly from year to year, mostly in relation to rainfall amount and distribution, it can be difficult to make comparisons between studies that are conducted in different locations or in different years. Indeed, few, if any, studies in New Zealand have measured nitrate leaching losses from commercial paddocks under different land uses in the same locality and season. The aim of this study was to compare nitrate leaching losses from commercial paddocks under three different land uses (receiving typical management practices) in the same year in the same district to assess the relative impacts of these land uses on potential groundwater nitrate contamination.

MATERIALS AND METHODS

Site and soil

The study was conducted from late June to early October 2000 on 18 commercial paddocks in the

Table 1 Nitrogen fertiliser applied before and during winter leaching, soil profile mineral contents before and after winter leaching, and cumulative leached N for the different land uses (all units are kg N ha^{-1}).

Land use	Paddock	Fertiliser applied before winter leaching	Soil mineral N before winter leaching[1]	Fertiliser applied during winter leaching	Soil mineral N after winter leaching[2]	Cumulative leached N[3]	Paddock leached N[4]
Dairy	D1	10	38	55	26	14	14
	D2	10	22	55	63	14	14
	D3	10	38	85	32	29	29
	D4	10	30	85	42	14	14
	D5	45	26	50	38	11	11
	D6	10	42	85	35	10	10
	Mean[5]	16	32	68	38	15	15
Potatoes	Unfert. area (P1)	0	65	0	25	40	40
	P1	0	39	472	216	122	89
	P2	472	470	0	75	295	193
	P3	472	622	0	247	204	138
	P4	414	158	77	48	134	96
	P5	414	145	77	52	152	107
	P6	414	148	77	106	79	63
	Mean[5]	364	184	117	101	164	114
Greens	Unfert. area (G6)	0	82	0	25	73	73
	G1	64	215	60	110	240	173
	G2	124	152	0	146	142	114
	G3	124	151	0	203	175	134
	G4	124	193	0	172	73	73
	G5	150	117	100	22	85	80
	G6	0	93	250	41	91	84
	Mean[5]	98	148	68	90	134	110
	LSR (d.f. = 30)[6]		2.0		2.0		
	LSD (d.f. = 15)[1]					60	

[1]For comparisons between land use means.
[2]Back-transformed from the log-transformed data (i.e., equivalent to geometric means).
[3]Calculated from soil solution nitrate concentrations and drainage beneath the fertilised area.
[4]Adjusted for fertilised and unfertilised areas (see text for details).
[5]For fertilised areas.
[6]Least significant ratio, for comparisons between land use means.

Pukekohe area (approximately 50 km south of Auckland), supporting either dairy farming, winter greens [spinach, cauliflower or cabbage] or winter potato production. All paddocks had well-drained Patumahoe clay loam soil (Orbell 1974), an allophanic oxidic granular soil in the New Zealand soil classification (Hewitt 1998). Sixteen of the paddocks were located within a 2-km radius, centred on the Crop and Food Research Farm in Pukekohe (NZMS 260 R12 756423). The other two paddocks (both growing greens) were located 15 km away. Six paddocks of each land use were selected, and all were managed by growers according to their standard practices. Each paddock had a long, documented history of its respective land use. For this region, mean annual rainfall is 1321 mm and mean annual drainage is 632 mm. On average, more than 60% of this drainage occurs between June and October (Anon. 1986). Daily meteorological data during the study was measured on the Crop and Food Research Farm in Pukekohe.

Paddock management

The six dairy paddocks (D1–D6) were on the same farm, under similar management practices. All dairy paddocks grew ryegrass (*Lolium perenne*)/white clover (*Trifolium repens* L.) pastures and had an average stocking rate for the whole year of 2.5 cows ha^{-1}. Each paddock was block grazed at approximately 250 cows ha^{-1} day^{-1} three times during the study. Cows were removed from these paddocks at night. Dairy shed effluent was not applied to these paddocks either before or during the study. Fertiliser N (10 kg N ha^{-1}) was applied to all paddocks in autumn (April/May), with additional fertiliser (25–35 kg N ha^{-1}) applied shortly after each grazing event. All fertiliser was surface broadcast, with a total of 65 – 95 kg N ha^{-1} applied to the dairy pastures between late April and October (Table 1).

The winter potato paddocks were located on two separate properties (P1–P3 and P4–P6), but all paddocks had very similar management practices. After each potato crop (harvested in October), paddocks were surface worked and sown with a cover crop of oats (*Avena sativa* L.). The oat crops were mulched before paddocks were ripped, mouldboard ploughed, and surface worked. Beds (1.6–1.7 m wide, with wheeltracks 60–70 cm between the beds) were then formed before potatoes were planted (between early May to mid June) and beds ridged. A total of 472–491 kg N ha^{-1} fertiliser was applied to the potato crop beds (which covered approximately 60% of each paddock's area). The majority (76% averaged over all the paddocks) of the fertiliser was applied at planting, at a depth 20 cm below the soil surface. The remainder of the fertiliser was applied as two small side dressings (each about 40 kg N ha^{-1}) during the growing season, which were surface banded over the beds. A fertiliser trial with four replicates was present in part of paddock P1, the unfertilised treatment of which was also sampled as part of this study.

The greens paddocks were also located on two separate properties (G1–G4 and G5–G6). Four of the paddocks (G1–G4) were growing spinach continuously, with the other paddocks growing either cabbage (G5) or cauliflower (G6) in a cabbage-cauliflower rotation. Cover crops were not grown in these greens paddocks. Between crops, paddocks were ripped, mouldboard ploughed, and surface worked. Beds (1.6–1.7 m wide, with wheeltracks 60–70 cm between the beds) were then formed before the greens crops were planted in mid to late June. A total of 124–250 kg N ha^{-1} was applied to the greens crop beds (which covered approximately 60% of each paddock's area). The majority (60% averaged over all the paddocks) of the fertiliser was applied at planting at a depth 10 cm below the soil surface. The remainder of the fertiliser was applied as one or two side dressings (total of 60–100 kg N ha^{-1}) during the growing season, which were surface banded over the beds. A fertiliser trial with five replicates was present in part of paddock G6, the unfertilised treatment of which was also sampled as part of this study.

For the potato and dairy paddocks, most of the N fertiliser was applied as urea, whereas the winter greens paddocks received a mixture of urea and calcium ammonium nitrate. Due to the rapid conversion of urea to ammonium and nitrate, the form of N in the applied fertilisers was not expected to have a major impact on the extent of N leaching during the experiment.

Postharvest residues from the previous crops were returned to the soil for both the winter greens and potato crops. The amount of N contained in these residues varied between crops (spinach = 13 kg N ha^{-1}; cabbage = 85 kg N ha^{-1}; cauliflower = 206 kg N ha^{-1}; potatoes = 5 kg N ha^{-1}) (C. S. Tregurtha unpubl. data).

Sampling and analysis

Soil samples were taken from all paddocks at the start and end of winter leaching, in late June and early October, respectively. The exception was paddock P1, from which the pre-leaching samples were taken in May. For each of the dairy paddocks, three sampling positions were randomly selected. For each of the potato and greens paddocks, three sampling positions were randomly selected within the fertilised areas. Additional samples were taken from the non-fertilised treatments of the fertiliser trials in paddocks P1 and G6. In all paddocks, two samples at each position were taken from 0–15, 15–30, and 30–60 cm depths. Each sample was thoroughly mixed, subsampled, and the field moist soil analysed for ammonium- and nitrate-N.

After planting, five porous ceramic samplers 25 mm wide and 55 mm long were installed to 60 cm depth in random locations within the fertilised areas in each of the potato and greens paddocks. Additional samplers (five per replicate) were installed in the non-fertilised treatments of the fertiliser trials in paddocks P1 and G6. Ten porous ceramic samplers were installed in random locations in each of the dairy paddocks. Soil solution samples were extracted within 24 h of each significant (>20 mm) rainfall event. Nitrate leaching losses were determined from mean soil solution nitrate concentrations at successive samplings and the calculated drainage between these samplings (Francis et al. 1992). The amount of drainage was calculated from a simple water balance based on measured initial soil moisture, daily rainfall, and evapotranspiration (Jamieson et al. 1995). Estimates of the crop ground cover were used to partition water use between transpiration and bare soil evaporation. Ammonium-N and nitrate-N in soil solution samples and soil extracts were determined as described in Francis et al. (1992).

Soil solution nitrate concentrations and cumulative nitrate leaching losses were analysed with analysis of variance (ANOVA). Soil mineral N data were analysed with ANOVA after first log-transforming the data (to make the variability more homogeneous across the treatments). In Table 1, the presented paddock and land use means for soil profile mineral N data are back-transformed from means of the log-transformed data. For each land use, therefore, the average of individual paddock back-transformed means is not the same as the presented land use mean. Similarly, for each land use the sum of the individual depth data in Table 2 is not the same as the presented land use profile mean in Table 1. Comparisons between land use means or depth means are made using the least significant ratio (LSR). The LSR is the smallest ratio between two back-transformed means (largest mean/smallest mean) such that the larger mean is significantly greater than the smaller mean. Between and within paddock variability were separately estimated within the analysis of variance, and differences between land uses were compared with the between paddock variability. Sample dates were included as a split-plot treatment in the analysis, and depths as split-split plot treatments. In the tables and graphs, only a selection of possible LSDs/LSRs are presented for simplicity.

RESULTS AND DISCUSSION

Rainfall and drainage

Total rainfall from late June to early October 2000 (512.8 mm) was fairly evenly distributed (Fig. 1) and was similar to the long-term average (524 mm) (Anon. 1986). Consequently, nitrate leaching losses from the trial paddocks are likely to be representative of long-term mean losses for the district. Calculated drainage amounts were also relatively evenly distributed throughout the trial period (Fig. 1). Drainage was similar for all land uses, as frequent

Table 2 Mean soil mineral N contents before and after winter leaching under fertilised dairy, potato, and greens paddocks. The presented means are back-transformed from the log-transformed data (i.e., equivalent to geometric means).

	Soil mineral N content (kg N ha^{-1})					
	Before winter leaching (cm)			After winter leaching (cm)		
Land use	0–15	15–30	30–60	0–15	15–30	30–60
Dairy	25.9	6.2	7.3	29.5	7.4	9.1
Potatoes	13.0	198.7	88.9	19.7	27.6	70.1
Greens	80.8	35.1	42.2	22.1	18.1	66.4
LSR (d.f. = 30)[1]		2.3			2.3	

[1]Least significant ratio.

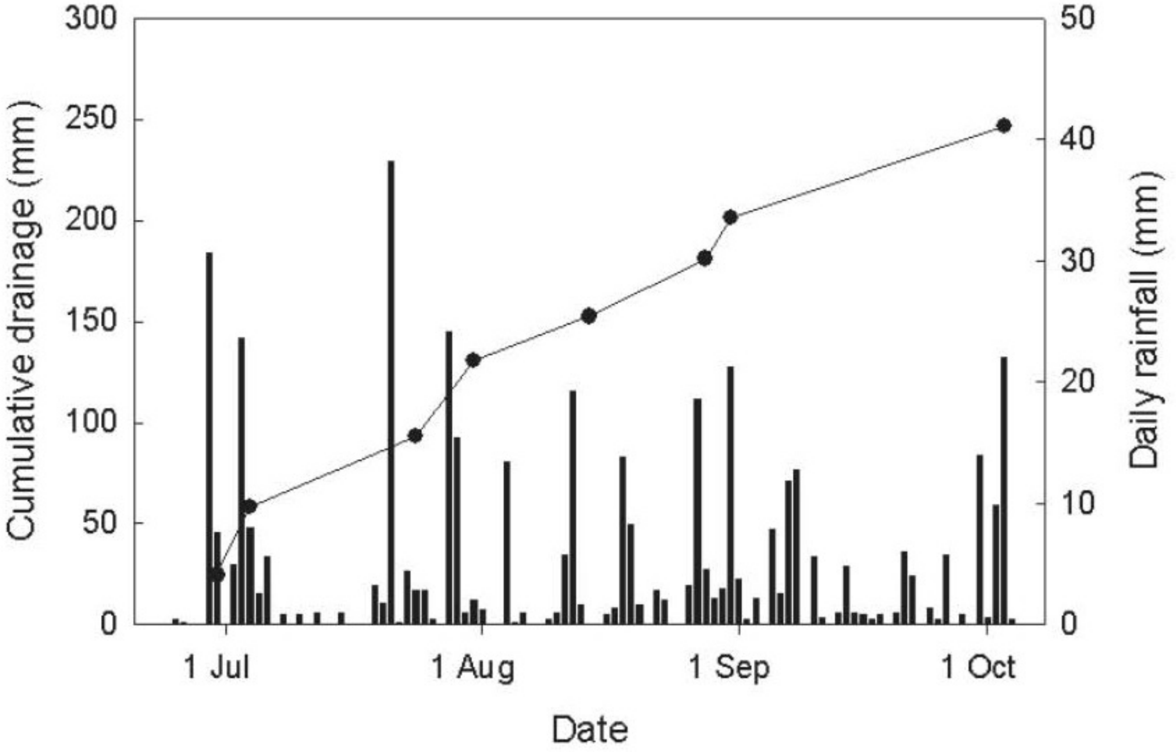

Fig. 1 Daily Pukekohe rainfall and cumulative winter drainage averaged for the three land uses in winter (late June–early October) 2000.

rainfall events and low evapotranspirative demand resulted in similar amounts of water being lost through transpiration and bare soil evaporation (Francis et al. 1998).

Soil mineral N contents

Mean soil profile mineral N contents before the start of winter leaching varied significantly between land uses. Dairy paddocks had the lowest contents, while fertilised potato paddocks had the highest contents (Table 1). These differences were largely the result of different N fertiliser application rates for the three land uses. The average N fertiliser rates applied to the different land uses in this study are typical of the Pukekohe district (Crush et al. 1997; Ledgard et al. 1999; de Klein & Ledgard 2001). In contrast, mineral N contents were low in the greens and potato paddocks to which no fertiliser had been applied before sampling. The range in mean soil mineral N content between paddocks under the same land use was relatively small (up to 20 kg N ha^{-1}) for the dairy paddocks, but very large (up to 477 kg N ha^{-1}) for the potato paddocks that had been fertilised before sampling (i.e., excluding paddock P1). The range in mean soil mineral N content between the greens paddocks that had been fertilised before sampling (i.e., excluding paddock G6) was intermediate (up to 122 kg N ha^{-1}). The small range in the dairy paddocks was due to the even, surface broadcasting of low rates of N fertiliser and uniform uptake of N by pasture. In contrast, the greater range for both the fertilised potato and greens paddocks probably resulted from variation in the application rate of the large amounts of fertiliser N that was applied before sampling. The uneven distribution across the paddock of postharvest residues from the previous crop may also have contributed to the range in measured soil mineral N content, especially for the cabbage and cauliflower paddocks.

The form and depth distribution of the soil mineral N before winter leaching varied between land uses. On average, most of the mineral N in the soil profile was present in the surface (0–15 cm) layer of dairy soil (Table 2), as N inputs from urine and fertiliser (mainly as ammonium) were applied to the soil surface. The rate of urea hydrolysis and

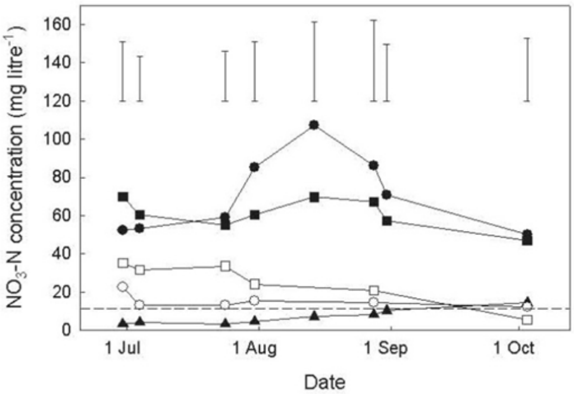

Fig. 2 Mean soil solution nitrate concentrations under fertilised dairy (▲), potato (●) and greens paddocks (■) and under unfertilised potato (○) and greens paddocks (□). Vertical bars represent LSDs (d.f. = 15) for comparisons between the different fertilised land uses at each sampling date. The dashed line is the New Zealand drinking water standard.

nitrification of ammonium was rapid at this depth, with almost all the mineral N present as nitrate (data not shown). In the potato paddocks, most of the mineral N was present at 15–30 cm depth. Fertiliser had been banded 3–6 weeks before sampling at 20 cm depth in these paddocks as either urea or ammonium. The applied fertiliser was still undergoing nitrification at the time of sampling as a large proportion of the soil mineral N was present as ammonium (data not shown). In the greens paddocks, some fertiliser (as urea, ammonium, and nitrate) had been banded at 10 cm depth and some fertiliser had been applied to the soil surface 1–3 weeks before sampling. As a result, most of the mineral N in the soil profile was present at 0–15 cm depth, with about 30% of it present as ammonium at this depth (data not shown). In the unfertilised areas of paddocks P1 and G6, soil mineral N contents increased with depth. The proportion of the mineral N at 30–60 cm depth was about 50% in the greens paddock and about 75% in the potato paddock (data not shown). All the vegetable paddocks used in this trial had a history of long-term cropping and would have had low organic matter and mineralisable N contents (Haynes & Francis 1990; Haynes & Tregurtha 1999). Recovery of applied N fertiliser by vegetable crops is often low (MacDonald et al. 1997), so it is likely that the mineral N in the unfertilised soil was partly unrecovered fertiliser N that had been applied to the previous crop and had subsequently been leached to this depth. In the cabbage and cauliflower paddocks, some of the mineral N may have originated from the large amount of crop residues that was returned to the soil when the previous crop was harvested. The residues of these vegetable crops have low C:N ratios, so rapidly mineralise when incorporated into the soil (De Neve & Hofman 1998; Rahn et al. 1998; Goulding 2000; Mitchell et al. 2000).

After winter leaching, mean soil profile mineral N contents were still significantly greater in the potato and greens paddocks than in the dairy paddocks (Table 1). Most of the soil mineral N was present as nitrate at all depths for all land uses due to nitrification of the applied fertiliser N between sampling events (data not shown). Between the sampling times, mean soil mineral N contents had stayed almost constant under dairy, but had decreased under both greens and potatoes. The soil mineral N contents in the unfertilised areas of paddocks P1 and G6 also decreased between the sampling events. The changes in soil mineral N content between sampling times were due to different amounts of leaching loss and crop uptake for the three land uses (see later). For dairy, the average distribution of mineral N was similar at both sampling times. For both the fertilised greens and potato paddocks there was an increase in the proportion of mineral N at 30–60 cm depth after winter leaching, due to the movement of nitrate down the soil during winter leaching. All land uses had similar soil mineral N contents at 0–15 cm depth, but there was significantly more mineral N at 15–60 cm depth under the fertilised greens and potatoes than under dairy land use (Table 2).

Soil solution nitrate concentrations and nitrate leaching losses

Mean soil solution NO_3-N concentrations at 60 cm depth were significantly greater throughout the trial under the fertilised potato and greens paddocks than under the dairy paddocks (Fig. 2). This was due to the greater soil nitrate contents in the fertilised potato and greens paddocks than in the dairy paddocks, especially deeper in the profile. Concentrations under the dairy and fertilised greens paddocks were relatively constant, whereas concentrations under the fertilised potato paddocks increased markedly during August. The increase in mean concentration in the potato paddocks would have been caused by the leaching to 60 cm depth of some of the very large amount of mineral N that was at 15–30 cm depth at the start of winter. Mean NO_3-N concentrations under the fertilised potato and greens paddocks exceeded the New Zealand Drinking Water Standard

(NZDWS) of 11.3 mg litre^{-1} (Anon. 2000) at all sampling events. High nitrate concentrations have previously been measured under crops of winter potatoes (Prunty & Greenland 1997; Waddell et al. 2000) and winter green vegetables (P. H. Williams unpubl. data). Such high concentrations are due to the very high rates of N fertiliser that are commonly applied to winter vegetable crops to maximise their marketable yield and value (Rahn et al. 1992). These crops have shallow (less than 60 cm deep) and sparse root systems and are very inefficient at recovering applied fertiliser N (Greenwood et al. 1989; Goulding 2000). Concentrations under the unfertilised areas of the greens and potato paddocks were lower than under the respective fertilised areas throughout the trial. Nevertheless, concentrations under the unfertilised paddocks also exceeded the NZDWS throughout most of the trial, probably due to unrecovered fertiliser N that had been applied to the previous crop and mineralisation of residues, especially from previous cabbage and cauliflower crops. In contrast, mean concentrations under the dairy paddocks were below 11.3 mg litre^{-1} throughout most of the trial.

Mean cumulative nitrate leaching losses were significantly greater throughout the trial from the fertilised areas of the greens and potato paddocks than from the dairy paddocks (Fig. 3), mainly due to the differing solution sampler nitrate concentrations under the three land uses (Fig. 2). Losses from the unfertilised areas in paddocks P1 and G6 were lower than from the fertilised potato and greens paddocks, but were higher than from the dairy paddocks. The mean cumulative loss over the winter (late June to early October) from the dairy paddocks in this study (15 kg N ha^{-1}) was lower than the estimated annual loss of 30–45 kg N ha^{-1} (Francis et al. 1999; de Klein & Ledgard 2001) from typical dairy farms (stocking rate 2.5–2.8 cows ha^{-1}; annual N fertiliser input 50–60 kg N ha^{-1}) or the measured annual loss of 20–74 kg N ha^{-1} (Ledgard et al. 1999) from Waikato dairy farmlets (stocking rate 3.3 cows ha^{-1}; no N fertiliser applied). In Pukekohe, however, only about 60% of the annual drainage and leaching occurs on average from late June to early October (Anon. 1986). Consequently, losses during winter only are expected to be lower than annual losses.

Losses from the fertilised land uses in Fig. 3 were calculated by assuming that 100% of the paddock area was covered by fertiliser. This was a reasonable assumption for the dairy paddocks in which fertiliser was surface broadcast. However, in the greens and potato paddocks, fertiliser was only applied to about 60% of each paddock's area. Consequently, for potato and greens land use cumulative losses averaged for the paddock were calculated as:

Paddock average loss = (FA × FL)/100 + (UA × UL)/100

Where FA and UA are the amounts of the paddock (in %) covered by the fertilised and unfertilised areas respectively, and FL and UL are the cumulative losses from the fertilised and unfertilised areas, respectively. Using this approach, mean cumulative losses were calculated to be 114 kg N ha^{-1} for the potato paddocks and 110 kg N ha^{-1} for the greens paddocks.

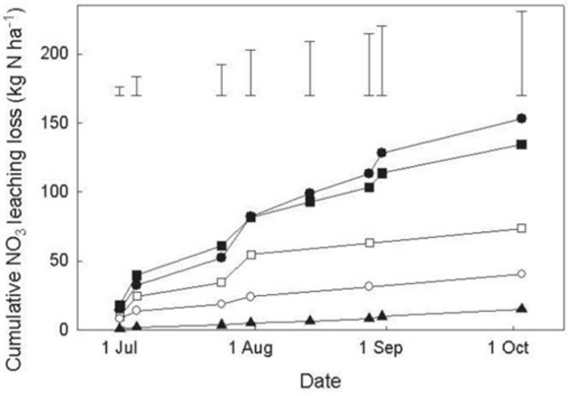

Fig. 3 Mean cumulative nitrate leaching losses from fertilised dairy (▲), potato (●) and greens paddocks (■) and under unfertilised potato (○) and greens paddocks (□). Vertical bars represent LSDs (d.f. = 15) for comparisons between the different fertilised land uses at each sampling date.

Cumulative losses from the potato paddocks in this study were similar to other measured losses of 80–115 kg N ha^{-1} from winter potato paddocks fertilised at rates of 308–520 kg N ha^{-1} and receiving average amounts of winter rainfall (P. H. Williams unpubl. data). Similarly, losses from spinach paddocks (G1–G4) in this study were similar to the reported loss of 140 kg N ha^{-1} from winter spinach in 1998 fertilised at a rate of 250 kg N ha^{-1} (Williams et al. 2000b). Losses from the cabbage and cauliflower paddocks (G5 and G6) were less than the reported loss of 178 kg N ha^{-1} for cabbage paddocks in 1999 that were fertilised at 150 kg N ha^{-1} (Williams et al. 2000b). This difference is not surprising, as leaching losses can vary substantially from year to year in relation to winter rainfall amount and distribution (Francis 1995). Winter rainfall in 2000 was similar to the long-term mean, whereas winter rainfall in 1999 was greater than the long-term mean. In addition, in 1999 more of the winter drainage occurred soon after planting than in 2000. Consequently, in 1999 the cabbage plants would have taken up very little N before drainage started, leaving more mineral N in the soil at risk of leaching.

The amount of N removed in animal products from the dairy paddocks was calculated at about 23 kg N ha^{-1} over the 4-month study. This figure is based on a 2-month dry period and a 2-month lactating period, during which periods mean pasture consumption was assumed to be 5.5 and 13.65 kg DM cow^{-1} ha^{-1} respectively (MAFTech 1987). The N content of the pasture was assumed to be 4% (de Klein & Ledgard 2001), with 80% of the consumed N returned to the soil as urine and dung (Haynes & Williams 1993). This calculation suggests that during the study period the N inputs were about 60 kg N ha^{-1} greater than the N removed in animal products, when averaged across the paddock. This is a relatively small difference and is consistent with the low mean N leaching losses from the dairy paddocks over the winter. However, most leaching losses from dairy paddocks occur from urine patches (Ledgard et al. 1999; de Klein & Ledgard 2001), as these localised areas have very high mineral N contents of up to 1000 kg N ha^{-1} (Francis et al. 1999)—well above the amount that can be rapidly taken up by the pasture. Nonetheless, as urine patches occupy only a fraction of the paddock's area (Haynes & Williams 1993), mean losses from dairy paddocks are usually relatively low, compared with cropping.

The ratio of crop N uptake to the amount of applied N fertiliser varied considerably between crops. The amount of N taken up by potatoes in the foliage, tubers, and roots was measured in paddock P1 at 114 kg N ha^{-1}, with over 95% of this N in the tubers (C. S. Tregurtha unpubl. data). As this was very similar to the mean N output in tubers of 115 kg N ha^{-1} from winter potatoes in the Pukekohe district (Crush et al. 1997), we expect that N uptake would have been comparable in all the potato paddocks in this study. Consequently, large N leaching losses were associated with this land use as the amount of N applied as fertiliser greatly exceeded the plant N uptake and removal in harvested product. The amount of N taken up in the tops and roots of the cauliflower crop (paddock G6) was 330 kg N ha^{-1} (C. S. Tregurtha unpubl. data). The total amount of crop N uptake was not measured in the other greens paddocks, but reported values for the Pukekohe district are 17–91 kg N ha^{-1} for winter spinach (Williams et al. 2002) and 190 kg N ha^{-1} for winter cabbage (P. H. Williams unpubl. data). Using these values for all the greens paddocks in this study, the N fertiliser inputs were similar to the expected crop N uptake amounts. These estimated N uptakes suggest that the risk of N leaching should be much lower from the greens than from the potato paddocks. However, measured leaching losses were comparable from the greens and potato paddocks, possibly because the amount of N returned to the soil in crop residues is greater for the greens (spinach = 13 kg N ha^{-1}; cabbage = 85 kg N ha^{-1}; cauliflower = 206 kg N ha^{-1}) than for the potato crops (5 kg N ha^{-1}) (C. S. Tregurtha unpubl. data). Consequently, the rapid mineralisation of residues from the previous greens crops may have contributed to the larger than expected nitrate leaching losses from the greens paddocks (De Neve & Hofman 1998; Rahn et al. 1998; Goulding 2000; Mitchell et al. 2001).

In the Pukekohe district, it appears that winter potato and winter greens production poses a greater threat to groundwater N contamination than does dairy farming. The actual contribution of these different land uses towards aquifer pollution will, however, depend on the proportion of the catchment area they each occupy. For the Pukekohe aquifer, similar areas are occupied by dairy farming (22%) and vegetable production (16%; Francis et al. 1999). For the winter potato paddocks, it is likely that a change in N fertiliser management is required to reduce the risk to N leaching. High rates of N fertiliser are commonly applied to winter potatoes as maximum yields and economic returns are shown to result at these high rates (Greenwood et al. 1989; Goulding 2000). Nevertheless, yields can be maintained at lower N fertiliser rates if N is applied strategically to match crop requirements rather than applied in one or two large applications (P. H. Williams unpubl. data). The estimated plant uptake for the greens paddocks suggests that the N fertiliser applications are reasonable. However, N derived from the rapid mineralisation of residues from the preceding greens crop is likely to contribute to the high soil mineral N contents and should be included in determining appropriate N fertiliser application rates to these crops.

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MODELING N-RESPONSE OF FIELD VEGETABLE CROPS GROWN UNDER DIVERSE CONDITIONS WITH N_ABLE: A REVIEW

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ABSTRACT

The development of advice on the use of nitrogen (N) fertilizers for vegetable crops in the UK is complicated by the numerous crops and the widely different ways in which they are grown. Modeling approaches have been adopted to provide cost effective means of solving the problem. It is based on fundamentally derived equations for groups of processes that dominate plant nutrition. The equations include ones for the decline in critical %N with increase in plant mass, for the dependence of growth rate on sub-optimal %N, and for the development of roots systems and their ability to extract nitrate from soil. They have been combined with those for soil processes into a model, N_ABLE, which calculates daily increments in N-uptake, growth, changes in the distributions of water and nitrate down the soil profile and the amounts of N leached out of the profile. It requires only readily available inputs; it has been calibrated for different crops and its validity tested against the results of field experiments. User-friendly versions have had an impact on commercial practices in the UK. An internet version enables simulations to be made for 22 different crops, grown on different soils, using either a user's own daily weather or best estimates of daily weather for any of 134 sites throughout the world. The model runs interactively at: http://www.qpais.co.uk/nable/nitrogen.htm

INTRODUCTION

More than twenty different vegetable crops, many of approximately the same monetary value, are grown in the UK. They are grown on contrasting soils and in different ways. It is impracticable to carry out fertilizer trials on more than a few of the possible combinations of soils and crops. Initially a "short-cut" approach to forecasting fertilizer-N requirements was developed in which it was assumed that the relative responsiveness of each crop was the same on all soils. The responses of each of the different crops were compared with the responses of one crop, potatoes, which had been grown in nation-wide experiments. These latter experiments were on soils with mineral-N supplying power, estimated by the then current advisory procedures in the UK. From these two sets of information and rather simple models, predictions were made of responses of all the vegetable crops in terms of N-supplying power on which they were grown. They were tested against the results of past experiments, and although the predicted response curves left room for improvement, it was felt they would be of interest to growers and they were summarized in leaflets that were in much demand (1).

This approach was only approximate as it failed to take account of many factors that influence N-response, including the daily rainfall and irrigation. Furthermore there was increasing public pressure to use fertilizers more efficiently so as to reduce pollution. The introduction of dynamic models for leaching (2) suggested how it might be possible to devise simulation models for N-response that took account of most of the major factors influencing it. Moreover relationships, with a sound scientific basis, for key processes at the whole crop level of detail were being discovered. It therefore seemed to be a good idea to combine these relationships into models that calculate the day-to-day changes in N-uptake, crop growth, distribution of mineral-N down the soil profile, and especially leaching into the drainage water. One such model that was developed is N-ABLE. It has been calibrated for 22 different crops and tested against the results of field experiments. Attention has also been paid to making it user-friendly with easily available inputs and to make it readily accessible. The aim of this paper is to review the crop nutritional principles on which this work was based and to discuss the presentation of the model to potential users.

QUANTITATIVE RELATIONSHIPS

Any dynamic model for crop response includes three plant nutritional components: crop demand, root development, and crop uptake of soil mineral-N, and each will now be discussed.

Crop Demand

Crop demand is the amount of mineral-N that must be absorbed to permit the potential maximum growth rate for a given aerial environment. It depends on the growth rate and the critical %N, the minimum %N needed for maximum growth.

Growth Rate

The commercial harvest date of most vegetable crops occurs well before growth rates decline as a result of approaching maturity. I will therefore consider growth until the onset of senescence. Let us first consider growth in a constant aerial environment of a crop drilled at the normal plant spacing in West Europe so that crop cover is quickly established. Let us also suppose that there is an ample supply of water and nutrients.

Growth increases with increase in the proportion of the incoming radiation that is intercepted by the leaves. In the early stages, interception and thus growth of dry matter increases roughly in proportion to plant dry weight; growth rate thus increases almost exponentially with time so that relative growth rate is almost constant. As the plants get bigger, however, the leaves overlap and the proportion of radiation intercepted per unit of plant weight declines. After plant dry weight exceeds about $2\,t\,ha^{-1}$ interception of radiation increases very slowly with increase in plant dry weight, and, in consequence, growth rate becomes almost constant.

These changes in growth rate have been mimicked for C3 field vegetables and some C3 agricultural crops by the equation:

$$dW/dT = K_2W/(K_1 + W) \quad [1]$$

where W is plant dry weight in t/ha, T is time, K_1 (usually set at $1\,t\,ha^{-1}$) is the value of W when growth rate is half the maximum and K_2, $t\,ha^{-1}\,d^{-1}$, is a growth rate coefficient (3). When W is small $K_1 + W \rightarrow K_1$, and the relative growth rate $(dW/dT)/W$ is almost constant. When W is large $K_1 + W \rightarrow W$ and growth rate, dW/dT is almost constant. Equation [1] thus closely matches theoretical expectations until senescence or the reproductive phase is reached when growth rate slows. Of course, in reality the coefficient K_2 will be affected by the intensity of radiation and by temperature. It has been found, however, that for UK crops during the main growing season, the effects are not great and a very good approximation to the growth of the crop throughout this period can be obtained by setting K_2 to a constant value when there is ample soil water. What is more, the value of K_2 is approximately the same, $0.2\,t\,ha^{-1}\,day^{-1}$ for many C3 vegetable and agricultural crops grown in the UK. Presumably, over the millennia, plant selection and breeding has led to many species having a similar growth rates and being insensitive to minor variations in the aerial environment (3).

Critical %N

Plants contain both nitrate-N and organic-N, but for the purposes of this discussion %N will be considered to be %organic-N within the plant, as the amounts of nitrate-N usually constitute only a small proportion of the total. Luxury consumption occurs in some root crops presumably because their wild ancestors needed to build up reserves for a subsequent reproductive phase. Let us focus, however, on the critical %N, the minimum needed to permit maximum growth rate. Generally most N is in the photosynthetic apparatus and comparatively small amounts are in the structural and storage tissues of plants. The photosynthetic material is a large proportion of total plant weight, and thus the %N is large in small plants. But as plants grow the structural and storage tissues constitute an increasing proportion of the total dry weight so that the %N of the entire plant falls. Thus the %N of seedlings is high whereas that of trees is small. Considerations such as these suggested that critical %N of crops might decline with increase in plant mass in much the same way as growth rate and that there might be widely applicable relationships.

One investigation concerned many C3 field vegetables grown at commercial plant densities in which crop cover is complete whilst the crops are still small. It was found that although there was some inter-species variation between critical %N, $N_{crit,}$ and W, the dry weight of the foliage and storage organs, N_{crit}, was related to W for many crops by:

$$N_{crit} = 1.35(1 + b_1 3e^{-0.26W}) \quad [2]$$

where b_1 is a crop dependent coefficient (4). Independently Lemaire (5) and his colleagues working with herbage and cereal crops (6,7) found that good fits to the experimental data could be obtained when $W > 1$ t/ha by

$$N_{crit} = aW^{-b2} \quad W > 1.0 \quad [3]$$

where a and b_2 are crop dependent coefficients. Although equations [2] and [3] appear to be very different, they give similar graphs of N_{crit} against W (for $W > 1\,t\,ha^{-1}$) when typical values of the coefficients for C3 crops ($b_1 = 3$, $b_2 = 0.5$ and $a = 5.7$) are substituted into the formulae (4,8). The values of the coefficients are remarkably similar for some species. This probably reflects the similarity in the dependence of their growth rates on plant mass per unit area resulting from the similarity in their photosynthetic apparatus, which contains most of the plant nitrogen.

It must be emphasized that the forgoing relationships refer to C3 crops. For C4 crops, like maize, the equation comparable to Equation [3] is (8)

$$N_{crit} = 4.1W^{-05} \qquad [4]$$

According to these equations the fractional decline in N_{crit} with increase in plant mass is the same for both C3 and C4 crops but C4 crops contain about 72% of the nitrogen in C3 crops at equivalent dry weights per unit area. As approximately 32% more dry matter is produced per unit area of intercepted radiation for C4 than for C3 crops (9), it follows that N-uptake, or weight of plant protein produced per unit of intercepted radiation, is approximately the same for both types of crop.

Further support for the wide applicability of these concepts is provided by evidence that the decline in critical and maximum % potassium (K) in vegetable crops falls with increase in plant mass in proportion to the decline in critical %N (10). Total plant cation concentrations decline linearly with critical %N as plants grow (10) and a strong link has been established between the decline in critical % phosphorus (P) and that of %N (11–13).

We have therefore useful relationships between critical %N, and possibly other nutrients, and plant mass per unit area that appear to apply to many different crops provided that they are grown at a spacing that ensures early completion of crop cover. If the plants are grown at wider spacings then the dependence of growth rate on critical %N is different (5).

Effect of Sub-optimal %N on Growth Rate

So far we have seen how growth rate, plant mass, critical %N, and interception of radiation by the crop canopy are all linked together. We can deduce the dependence of growth rate on sub-optimal concentrations of %N in plant tissues. A major step forward was made by Caloin and Yu (14) who put forward a novel framework for the various processes. They suggested that plants could be considered as consisting of just two components: (a) a photosynthetic component—the amount of which is proportional to the photosynthetic rate of dry matter production; and (b) a structural component, which includes storage tissue. They also considered that the %N in each component had different values, each of which remained constant throughout growth. From these premises and without any further assumption they deduced that:

$$N = N_0 + b \cdot R_{rgr} \qquad [5]$$

where N is the %N in the entire plant, R_{rgr} is relative growth rate, N_0 is the %N in the plant when growth ceases and b is a coefficient.

In some interruption experiments a curvilinear relationship, not a linear relationship, was found between total %N and R_{rgr} [e.g., Burns (15)]. It appears, however, that in these cases NO_3-N constituted a substantial proportion of the total-N in the plant (16). When there is a growth-limiting N-supply, theoretical, laboratory, and field experimental evidence supports the view that Equation [5] is a good approximation, at least for many situations (17–20). For the purpose of developing our model we need to determine the ratio, R_g, of the growth rate of a plant with a sub-optimal %N to that of a crop of the same weight, but containing the critical %N, N_C. This can be deduced from Equation [5] as

$$R_g = (N - N_0)/(N_c - N_0) \qquad [6]$$

where N_0 is as defined previously as the %N below which growth ceases.

Root Development

Root development can be affected by nutrient and water stress, by the onset of flowering, and in the case of potatoes, by tuber development. The primary purpose of roots is to obtain nutrients so it might be argued that unless the forgoing stresses are severe, root development of field crops will be dominated by crop demand for nutrients and the way it declines as the crop gets larger. Support for this view comes from root length measurements made at intervals during the development of some field vegetable crops grown in the same experiment with optimum supplies of nutrients and water. Figure 1 shows that measurements for several field crops follow the same linear relationship between ln L and ln W where L is root length in $km\,m^{-2}$. The relationship may be written as:

$$\ln L = B \cdot \ln W + \ln C \qquad [7]$$

where B and C are coefficents.

N-uptake U_n for plants with the critical %N is given by multiplying equation [3] by W. Taking logarithms gives

$$\ln U_n = B_2 \cdot \ln W + \ln a \qquad [8]$$

where B_2 and a are coefficients.

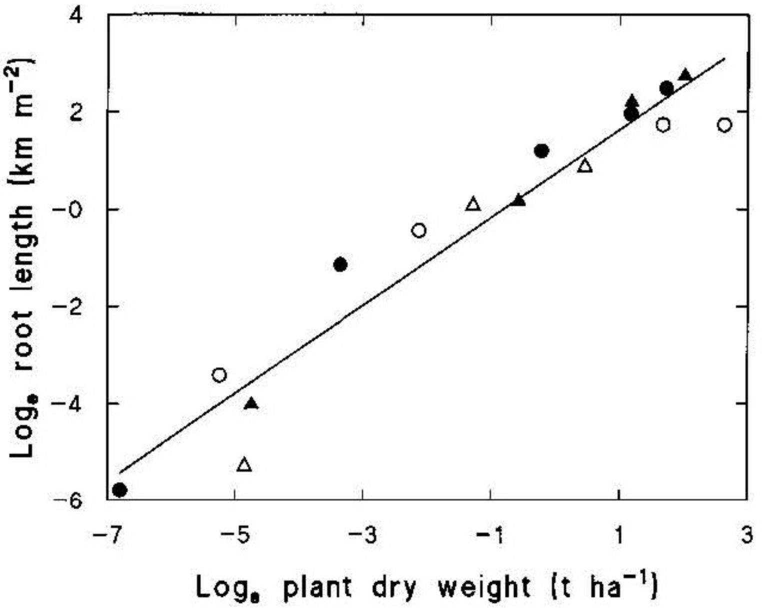

Figure 1. Relationship between ln root length (km m^{-2}) and ln plant dry weight (t ha^{-1}) for cauliflower (●), lettuce (△); parsnip (○) and turnip (▲) derived from data given in Greenwood et al., 1982.

It follows from equations [7] and [8] that

$$dL/L = m \cdot dU_n/U_n \qquad [9]$$

where $m = B/B_2$ and thus is constant.

In consequence the relative increase in root length is proportional to the relative increase in nitrogen uptake.

Another principle appears to govern the development of roots down the soil profile. Root length density appears to decline exponentially with depth (21,22) and, in consequence, the depth of soil containing say 90% of the roots, X_{90} (cm), is easily measured. For a range of field vegetable crops grown on a sandy loam soil it was related to plant dry weight (t/ha) by the following (22):

$$X_{90} = 17.1 + 8.89 \cdot W \qquad [10]$$

This means that the depth of soil containing 90% of the roots increased by about 10 cm for every increase of 1 t ha^{-1} of plant dry weight. Thus when W = 8 t ha^{-1}, X_{90} is about 90 cm. The dry weight of many crops far exceeds 8 t ha^{-1} so many crops would be expected to extract at least some water and nutrients from considerable depth in soil.

Nitrate Uptake

Both NH_4- and NO_3-N exist in soil. Nearly all the nitrogen in rice paddy soils and in acid soils is NH_4-N but in most European arable soils NH_4-N is rapidly converted to NO_3-N. So in NO_3-N is the main form in which crops absorb nitrate from these soils.

Roots of nitrogen deficient plants can readily absorb nitrate from very low concentrations in the rooting media. When such plants are grown with their roots in solutions that flow rapidly past them they absorb nitrate at a rate that is largely unaffected by concentration until it falls to very low concentrations, ca. $0.2\,mg\,N\,l^{-1}$ (23,24). In these experiments nitrate concentrations at the root surfaces are approximately the same as in the bulk of the solution. In soil, however, transport of nitrate from the bulk of soil to the root surfaces is slower so it might be expected that there could be substantial differences.

Nitrate is transported through the soil by diffusion and in the transpiration stream (mass or convective flow). An equation that has a sound theoretical basis has been derived for these processes [e.g., Burns (23)]. It indicates that the minimum concentration of soil nitrate needed to meet demand is insensitive to root length, is proportional to inflow rate, and is inversely proportional to soil water content. More importantly it suggests that if the soil is moist then only a proportion of the roots is required to meet crop demand for nitrogen unless the concentration falls to a low level (25,26). Of course if the soil is dry then crop growth will be small as will the crop demand for nitrogen and the ability of the soil to transmit nitrate to the roots. So generally low soil moisture will seldom be expected to induce N-deficiency. The exception is when some roots are in a wet zone containing no nitrate and remaining roots are in a dry zone that contains nitrate.

Although soil nitrate can be unevenly distributed down the soil profile, uptake of nitrate is remarkably insensitive to the way it is distributed throughout the rooting depth. Burns (23), in a comprehensive review of the literature, showed that when nitrate was withheld from most of the rooting media, roots in those regions that contained nitrate rapidly increased both their nitrate uptake rates and their rate of root growth in those regions. So after a lag phase, of variable duration, the rate of nitrate uptake of the entire root system became similar to those of control plants with their entire root systems in nitrate containing media, conclusions that are amply confirmed by more recent work (e.g., 27–29). Especially important are the findings that in field experiments yields are generally insensitive to the distribution nitrate down the soil profile (e.g., 23,30–32).

The rate at which roots absorb nitrate can be limited by the rate at which roots can transport nitrate from the surfaces to the xylem. Using the published maximum rate, Burns (23) calculated the minimum percentage (P_{min}) of the entire plant root system required to meet crop demands. It varied somewhat depending on the species, but most values had P_{min} less than 15%. He argued that as an approximation, nitrate availability to plant roots could be regarded as being related by a stepwise function. Above a critical depth nitrate was equally available to the roots but at greater depths it was unavailable to them. The critical depth was defined by: $(100 - P_{min}/2)$ (the depth of rooting).

This concept is central to N_ABLE. In this model it is considered that all the mineral-N above a certain minimum concentration is available to a depth of soil containing 90% of the roots (X_{90}). The minimum concentration is considered to be low, between 20 and 40 kg N m^{-1} ha^{-1}, depending on the crop and soil, and represents nitrate that is occluded in pockets of soil that are inaccessible to roots. It is further assumed that no nitrate at a depth below X_{90} is available to the crop.

As has been argued previously from Equation [7], the depth of soil containing 90% of roots increases to over 90 cm for a crop of about 8 t ha^{-1} dry matter. This yield is far less than the maximum of 20 t ha^{-1} that has often been achieved in West Europe. We would therefore expect that all the nitrate to a depth of 90 cm, above a low critical value, would be available for uptake by most crops and this expectation is born out by much field experimental evidence (33–35). Indeed, adjustment of N-fertilizer levels for differences in nitrate concentrations to a depth of a meter (N_{min}) has long been practiced for deeper rooting crops (36,37).

Crop N-Uptake

N_ABLE determines the actual uptake of nitrate for each day, as whichever is the smaller, the crop N-demand for that day or the amount of available nitrate within soil to the depth of 90% rooting at that time. Crop N-demand for the day is defined as the maximum amount of N that the plant could contain at the end of the day if it grew at the maximum possible rate, less the amount of N at the start of the day. In the absence of luxury consumption, the amount of N that the plant could contain at a given time is the product of critical %N and dry weight.

There is one other complication that deserves attention. It is that the daily increase in N in the above ground parts of a crop is less than the drop in the amount of soil nitrate even when there are no losses from leaching, denitrificaton or volatilization of ammonia. The apparent disappearance probably results from absorption into root material and from N-immobilization in the rhizosphere. Thus only a fraction of the apparent disappearance of soil nitrate is recovered as plant nitrogen. The value of the fraction depends on the species and declines with increasing levels of soil mineral-N (38).

THE MODEL-N_ABLE

From the foregoing information it is possible to formulate a model for a simplified system in which plants are growing in soil that contains a given amount of nitrate. We assume that there is no mineralization and that no nitrate is lost from the soil apart from that associated with crop uptake. To start the simulation it is necessary to have initial values of the distribution of available nitrate down the soil profile, the initial plant dry weight, and the %N in the plant. Then for each day the following are calculated:

1. The potential maximum increment in dry plant weight (from the existing weight, assuming no restriction from N-deficiency) and the potential maximum dry weight (Equation [1]);
2. The potential maximum N-uptake calculated from the product of potential maximum dry weight (see above 1) above and the critical %N for a crop of that size (Equation [3], from which is subtracted the N-content of the plant on the previous day (see below));
3. The actual uptake; this is whichever is the smaller—the potential maximum uptake (see above 2) or the amount of available nitrate in soil to the depth of 90% rooting (see 6 below);
4. The actual %N in the plant—calculated from the uptake in 3 above, the amount of N in the plant on the previous day, and the dry weight of the plant calculated for the previous day in 5 below;
5. The actual increment in weight and a new value for total dry weight increment in dry weight from its current dry weight and the calculated %N (Equations [1] & [6]).
6. The depth of soil containing 90% of the roots of a plant of that size (Equation [10]);
7. The amount of available nitrate to the depth of rooting after subtracting the amount of nitrate taken up by the crop (see 3 above).

Each of these calculations is repeated for each day during the growing period.

In addition to the key processes described above, it was also necessary to include in N_ABLE sub-models for soil and other plant processes (34). They included ones for evapo-transpiration, nitrification, the apparent recovery of soil mineral-N by the crop, the movement of water and of nitrate up and down the soil profile, the release and immobilization of mineral-N during the breakdown of endogenous soil organic matter and of crop debris from the previous crop, and the dependence of crop growth on the weather conditions. Account was also taken of luxury consumption. A simplified flow diagram of the model is given in Figure 2.

Estimates of crop dependent parameters were obtained, from field experiments, for 22 different vegetable crops and farm crops [e.g., (39)]. The validity of the model has been tested against the results of independent experiments [e.g., (40–42)]. An example of the degree of agreement obtained in one such experiment (43) is given in Figure 3.

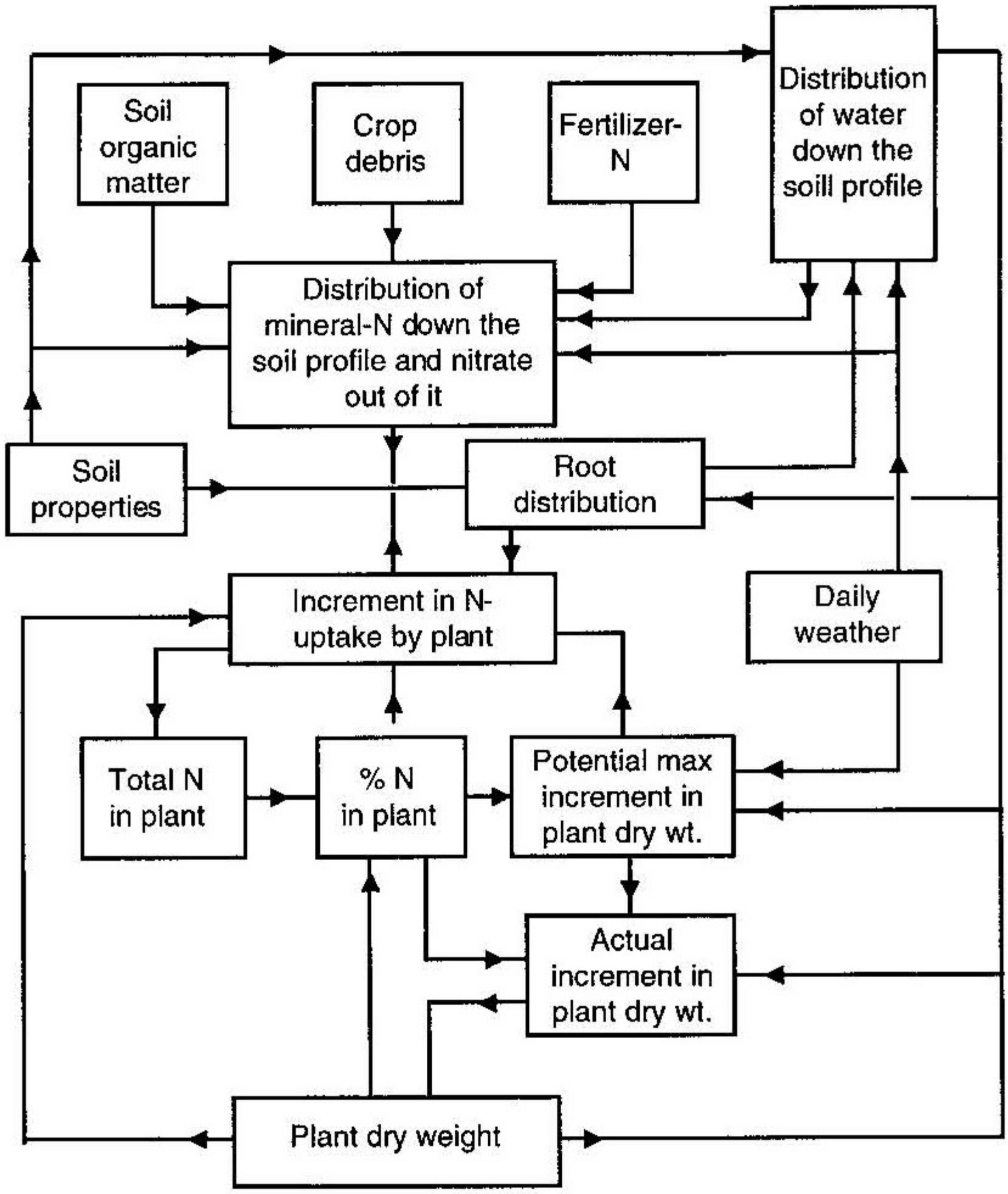

Figure 2. Simplified flow diagram of the processes in N-ABLE. Boxes represent variable quantities or groups of quantities; lines and arrows represent the interdependence of the variables.

APPLICATION

The inputs to N_ABLE are easily available. They are:

(a) Rainfall, evaporation from an open water surface and temperature for each day during the simulation;

(b) Estimates of soil moisture deficit, the distribution of mineral-N down the soil profile before drilling, and the times when they were made;

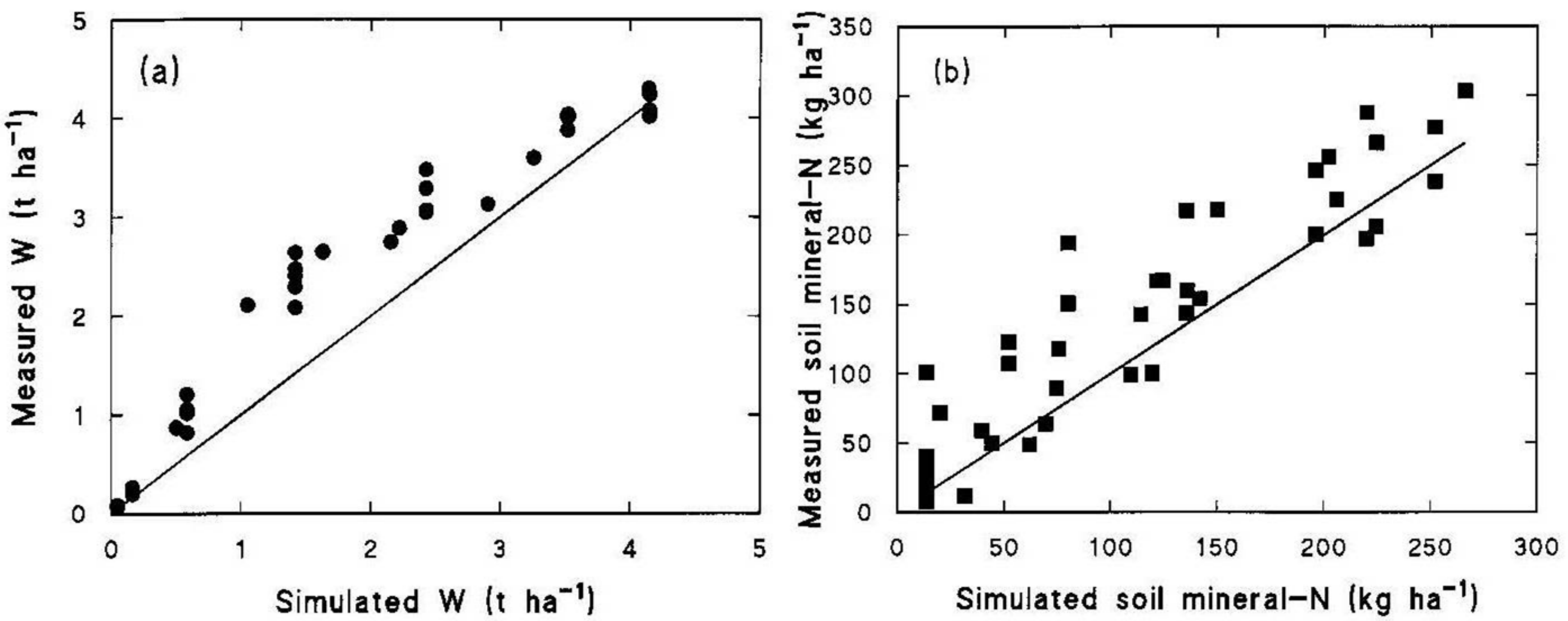

Figure 3. Test of the validity of N-ABLE with data from a multiharvest multilevel field experiment on lettuce. Simulated and measured (a) dry weights and (b) soil mineral-N to a depth of 30 cm from soil surface. Derived from Figures 4d and 5d of Yang et al., 1999 with kind permission from Kluwer Academic Publishers. Lines are those for perfect agreement.

(c) The times of incorporation of crop residues, of applying fertilizer-N, of drilling, and of harvest;
(d) Dry weights of drilled seed and of the expected maximum weight of plant dry matter of the crop, and the dry weight of crop residue of the previous crop (and its C/N ratio) incorporated in soil prior to cropping;
(e) The base and top dressing applications of fertilizer-N;
(f) Mineralization rate at a given temperature or, if this is not available, the % soil organic-C and the percentage of particles less than 20 μm to permit its calculation (44);
(g) The depth of any barrier to rooting.

One version of N_ABLE has been tailored to meet the needs of UK vegetable growers and their consultants. It is called WELL_N (45) and is supplied by the Horticultural Development Council, 18 Lavant Street, Petersfield, Hants GU32 3EW, UK.

An Internet version of N_ABLE can be run interactively and quickly free of charge on the Internet at http://www.qpais.co.uk/nable/nitrogen.htm

It can be run with any of the "best estimates" of daily weather for 134 sites throughout the world, or alternatively with the user-own weather data. Any of 22 different crops can be selected from a pull down menu, and a table of default values, which can be easily altered by the user, are given for the input parameters. The model usually takes less than 2 minutes to run after which various tabular and graphical outputs are offered. In addition the site gives fully referenced details of the model and the method of obtaining "best estimates" of daily weather. The model has been run thousands of times from all over the world and has prompted Internet discussion leading to opportunities for improvement. There is also an Internet version of a dynamic potassium model, and a prototype phosphate model has been devised and will hopefully be running shortly.

ACKNOWLEDGMENT

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Reading 3.3.5

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Evaluating a crop nitrogen simulation model, N_ABLE, using a field experiment with lettuce

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Key words: dry weight, lack of fit test, model evaluation, nitrogen simulation model, residual error, soil mineral N.

Abstract

A field experiment with lettuce was carried out to evaluate the simulation model, N_ABLE, which has been widely used to predict soil mineral nitrogen requirements and potential leaching hazards for vegetable and arable crops in England and parts of Western Europe. Plant and soil were sampled regularly and dry weight (*W*), percent N in dry matter and soil mineral N (*soil-N*) were measured. Measured *W* and *soil-N* were compared with data simulated using N_ABLE both during growth and at final harvest. Dry weight followed an asymmetrical S-shaped curve when the growth period was either 57 or 61 days for all N levels. This implies that N_ABLE, which assumes a J-shaped growth curve, can only be used in the first three-quarters of the growing period. Simulated *soil-N* in the 0–30 cm layer corresponded well with measured values throughout the experiment when parameters for the recovery of soil mineral N (*REC*) and mineralisation rate of soil organic-N (*NR*) were set at 0.70 (i.e. 70%) and 0.86 kg ha^{-1} d^{-1} respectively, both calculated from field data, and were higher than default values. For longer periods of growth, the best fit was obtained using a modified asymmetrical S-shaped growth curve equation $dW/dT = k_2 W\ G_f\ G_k\ /(1+W)$, where k_2 is a growth rate coefficient, G_f (≤ 1) is a correction coefficient to allow for any restriction in growth rate caused by sub-optimal%N in the crop and $G_k = (W_k/W)^n$ is another correction coefficient to adjust the growth rate which is decreased caused by genetic or other reasons in the later part of the growth period. The S-shaped equation was examined by a lack of fit test, and the results showed that the residual errors ($SS_R = \sum(y\text{-}x)^2$, where x =simulated values, y = measured values) were not significantly different from experimental error, indicating that the S-shaped equation gave a good description of growth for the different N levels through the growth periods.

Introduction

There are indications that simulation models will be more widely used to analyse complex cropping systems (Jones, 1990), as models provide information which is unobtainable from experimental procedures (Angus et al., 1993; Singh & Thornton, 1992). However, the process of model validation is considered as one of the most perplexing aspects of modelling (O'Leary & Connor, 1996a, b; Welch et al., 1981; Whitmore, 1991). In the last decade, several workshops have been held in the Netherlands to compare the performance of dynamic nitrogen models in crop and soil (De Willigen & Neeteson, 1985; Groot & Verberne, 1991) and for prediction of potato yield using a single data set (Kabat et al., 1995; MacKerron, 1992). Recently, Barnett et al. (1997) compared 3 major wheat models, AFRCWHEAT (UK), CERES (U.S.A) and SIRUS (New Zealand), using a powerful data set from more than 1000 wheat trials in the UK covering an 18-year period from 1975. An even more extensive comparison of five models is given by Jamieson et al. (1998). Many validations have also been made in which an individual model has been tested with different data sets (Addiscott & Whitmore, 1987; Graf et al., 1991).

N_ABLE is a deterministic dynamic nitrogen simulation model designed by Greenwood et al. (1996a) to simulate the growth of 24 vegetable (including lettuce) and arable crops in England and Western Europe. The model was described by Greenwood et al. (1996b) and incorporates the relationships for crop N concentration as described by Greenwood & Draycott (1989b) and Greenwood et al. (1986). Validation of N_ABLE has been carried out in England (Greenwood & Draycott, 1989a; Greenwood et al., 1992), in the Netherlands (Greenwood et al., 1985), in Belgium (Greenwood et al., 1987) and in Norway (Riley & Guttormsen, 1994). The results show reasonably good agreement between simulated and measured data, but some differences need to be explained, and currently validation is at the stage where it is difficult to find a good data set to check the relationship of daily dry weight (*W*), growth rate and soil mineral N (*soil-N*) distribution during the growing period. Further field experiments are therefore required. The objective of this paper is to test and evaluate the growth function in N_ABLE using data from a field experiment with lettuce.

Material and methods

Experimental design and field management

A nitrogen experiment with lettuce was carried out on light sandy loam soil during April – July 1997 at the University of Reading's Sonning Farm in the South of England (51° 27'N, 0° 56'W). The experiment was designed to compare measured and simulated dry weight growth curves and soil mineral N distribution patterns. It included ten nitrogen treatments of which six were sampled regularly to estimate the dry weight growth curve and soil mineral N distribution and the other four were used to calculate model parameters. There were three replicates each with three randomised blocks, and the plot area was 6.48 m^2. The experimental design and irrigation schedule are shown in Table 1.

Ammonium nitrate was applied to plots as basal and top dressings. A sufficient basal dressing of P, K fertiliser was applied in the previous autumn (9 October 1996), using 33 kg P ha^{-1} as triple super phosphate and 86 kg K ha^{-1}as potassium chloride based on MAFF (1994) fertiliser recommendations. Lettuce plants were raised by a commercial company in peat plugs for four weeks, then were transplanted on 21–22 May at a plant spacing of 30 × 30 cm into plots protected from birds and rabbits, and harvested on 22 July in a marketable condition. Overhead irrigation was given whenever the model predicted that the soil moisture deficit exceeded 30 mm. Normal cultivation management maintained the plots free of weeds. Two weeks after transplanting, cockchafers (*Melolontha meldontha*, L.) were found on the roots and the plants were treated with insecticide (gamma-HCH) followed by a water wash (MAFF Leaflet 35, 1983).

Samples and laboratory analysis

Plants were sampled (cut at ground level) at 7–10 d intervals from the N_0, N_{50}, N_{A180}, N_{B240},N_{C240} and N_{310} plots starting one week after transplanting. Six plants were cut in the samplings before 30 days after transplanting and three plants after that date. Fresh plant samples were weighed in the laboratory and dried at 80 °C for 72 h for dry weight measurement. The dry plants were ground for N analysis. Soil samples were taken on the same day or one day after plant sampling depending on the time available from 0–30 cm depth with a soil auger from 8 randomised points in three rows of each plot. Soil samples were transferred to the laboratory immediately after sampling, and a 10 g soil sample was used (3 replicates) to determine soil water content. 40 g of moist soil was shaken with 200 ml of 1 m KCl for one hour and the extract was analysed for ammonium and nitrate. Ammonium and nitrate were measured separately using a Perstorp 5010 Analyser. The sum of ammonium and nitrate corrected for soil water content was converted to *Soil-N* (kg N ha^{-1}) assuming soil weights of 4500 t ha^{-1}.

Results and discussion

Input parameter calibration

Simulation was by N_ABLE with input data collected from the field experiment. The weather data were from the meteorological station 100 m from the crop area. Mean air temperature was 15°C, total rainfall was 82 mm and total potential evaporation was 208 mm during the growing period. A crop-dependent parameter, the apparent recovery of soil mineral N when an infinitely small amount of fertiliser is applied (*REC*) and a soil dependent parameter, mineralization rate of soil organic N (*NR*) were calculated from field data. The field input parameters for running N_ABLE are listed in Table 2.

The first simulation was run using default values of *REC* = 0.52 and *NR* = 0.7 kg ha^{-1} d^{-1} as in N_ABLE

Table 1. Experimental design of the lettuce experiment

Days after transplanting	0	8	9	22	35	48
N application	Basal			Top-1	Top-2	Top-3
N treatment (kg ha^{-1})						
N_0						
N_{50}	30			20		
N^{a}_{A180}	80			50	50	
N_{B240}	180			60		
N_{C240}	70			120	50	
N_{310}	180			60	70	
N_{100}	80			20		
N_{200}	80			120		
N_{300}	80			120	100	
N_{400}	80			120	100	100
Irrigation (mm)		12.5	12.5		10	5

[a]$N_{A\ 180}$, $N_{B\ 240}$ and N_{C240} were considered to be possible economical N fertilizer treatments, and the shortened forms N_A N_B and N_C have been used in the text discussion.

Table 2. Field input parameters for N_ABLE, state variables and statistical terms

Abbreviation	Definitions	Values	Range
Input parameters			
FC	Field capacity, 0–30 cm (cm^3 water cm^{-3}soil)	0.20	
REC	Apparent recovery of soil mineral nitrogen	0.70	0.52 – 0.72
NR	Mineralization rate of soil organic N (kg ha^{-1} d^{-1})	0.86	0.70 – 1.30
W_p	Dry weight at transplanting (t ha^{-1})	0.01	
W_k	Dry weight at day T_k (t ha^{-1})	2.58	
W_{MAX}	Maximum dry weight at harvest (t ha^{-1})	4.30	2.50 – 4.30
T_p	Time of transplanting (days from 1st January)	141	
T_k	Time at which plant growth rate slowed down (days after transplanting)	43	
T_h	Time of harvest (days after transplanting)	61	42 – 61
N_P	Soil mineral N, 0–30 cm at transplanting (kg ha^{-1})	38	
State variables			
W	Dry weight above ground (t ha^{-1})		
Soil-N	Soil mineral nitrogen ($NH_4^+ + NO_3^-$) in the 0–30 cm layer (kg ha^{-1})		
Statistical terms			
SS	Sum of squares		
DF	Degrees of freedom		
F	Ratio of *SS* over *DF*		
Suffixes in statistical terms			
R	Items from residual		
E	Items from random error		
LF	Items from lack of fit		

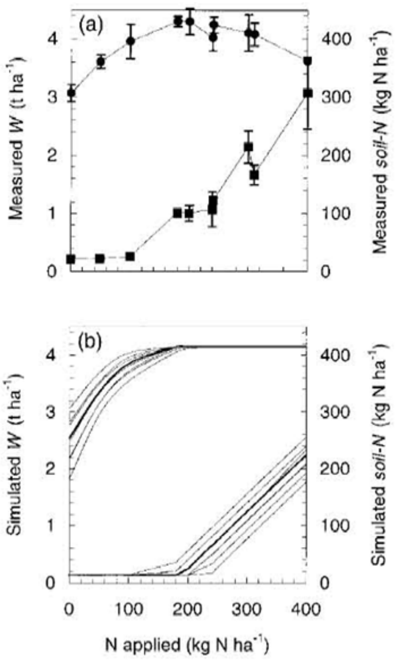

Figure 1. Comparison of measured and simulated dry weight response and *soil-N* distribution at final harvest (T_h = 61); (a) Symbols • are measured dry weight, ■ are measured *soil-N* (means of 3 plots and standard error). (b) The upper group of curves shows simulated dry weight response to fertiliser-N and the lower group of curves shows the *soil-N* distribution. Each group has 8 curves for 2×4 combinations of *REC* = 0.52, 0.72 and *NR* = 0.7, 0.9, 1.1, 1.3, e.g. the bottom curve of each group is for *REC* = 0.52 and *NR* = 0.7 (default). The dark curves are for *REC* = 0.72 and *NR* = 0.9.

(Greenwood et al., 1996a). From the output of dry weight and soil mineral N in the 0–30 cm layer, it was found that simulated *W* was significantly lower than the measured values in the lower N fertiliser plots (< 200 kg N ha^{-1}), while measured *soil-N* was significantly lower than the simulated values in higher N plots (> 200 kg N ha^{-1}). Previous sensitivity analysis (not published) had shown that both *W* and *soil-N* were sensitive to *REC* and *NR*. Therefore, the effects on *W* and *soil-N* of varying *REC* from 0.52 to 0.72 and *NR* from 0.7 to 1.3 were explored to identify the extent to which they affected *W* and *soil-N*. A satisfactory improvement in simulation was achieved by setting *REC* and *NR* at higher values although this had no influence on *W* at the higher N fertiliser applications or on *soil-N* at lower N fertiliser applications (Figure 1). Therefore, the field values of *NR* and *REC* need to be calculated from the field data for the simulation.

Calculation of REC and NR from the field data

REC was calculated from field data using N_0, N_{100}, N_{200}, N_{300} and N_{400} treatments based on the difference method defined as $REC = (N_U - N_{U0}) / N_F$, where N_U is the N uptake from plots receiving N, N_{U0} is N uptake from the N_0 treatment and N_F is fertiliser N applied on each N_U plot. A regression equation $REC = REC_0 - b\,N_F$ was then calculated. The value of $REC = REC_0$ when $N_F = 0$ was used as the *REC* input parameter in N_ABLE (Greenwood et al., 1989c, 1996a). Our result was $REC = 0.6974 - 0.0014\,N_F$, from which the value of $REC = 0.70$ was derived.

NR was derived by the regression method as used by Greenwood et al. (1996b). First, a regression equation $(N_U + Soil\text{-}N) = 79.18 + 0.87\,N_F$ was developed to calculated the apparent mineralised-N in the N_0 plot, and what fraction of soil mineral N can be accounted by $(N_U + Soil\text{-}N)$ at harvest, where $(N_U + Soil\text{-}N)$ values are the measured N uptake plus *soil-N* at harvest in different N fertiliser plots, and $d(N_U + Soil\text{-}N)/d\,N_F = 0.87$ means that a fraction of 0.87 of fertiliser N was accounted for by the values of $(N_U + Soil\text{-}N)$ at harvest. It is assumed that soil mineral N can be accounted for by the same fraction (0.87) in the N_0 plot, meaning that actual values of $(N_U + Soil\text{-}N)$ in the N_0 plot should be $(N_U + Soil\text{-}N)/0.87 = 79.18/0.87 = 91.01$ ($N_F = 0$). Another regression $(N_U + Soil\text{-}N)/0.87 = 21.4 + 0.72T_i$ was then developed for the N_0 plot, where T_i is the number of days from soil sampling to harvest, $(N_U + Soil\text{-}N)/0.87$ is the total amount of mineralised-N at time T_i and 0.72 is the mineralisation rate of soil organic-N, *NR*, in kg N ha^{-1} d^{-1} with a mean temperature of 13.31°C during the time T_i. This value of *NR* was adjusted to 0.86 kg N ha^{-1} d^{-1} at 15.9°C assuming it is proportionally related to temperature (Greenwood et al., 1996b). These values of *REC* and *NR* have been used in the following calibration and evaluation of the model.

Evaluating the model outputs with experimental data

Growth curve evaluation

In general, the simulated *W* growth curves are all J-shaped (exponential), while the measured *W* growth curves are all S-shaped for the whole growing period (e.g. dashed lines of Figure 2). Simulated *W* is well fitted to measured *W* for the early stage of growth and at final harvest. Systematic errors between simulation and measurement appear in the middle of the growth period (Figure 2). The reason why the simulated curves follow a J-shape for all N treatments is

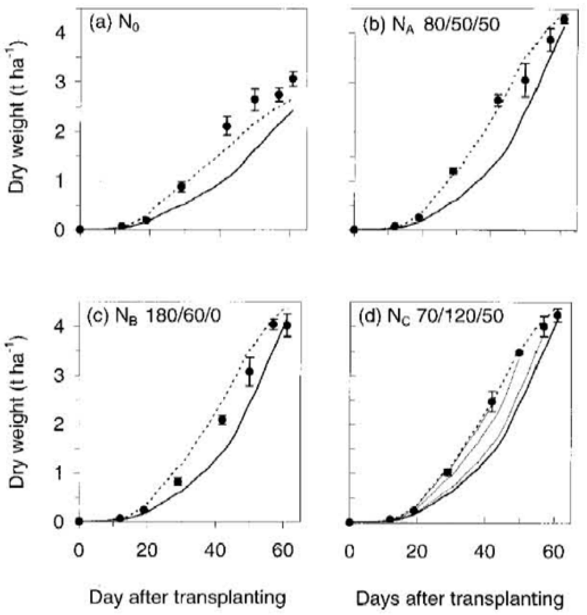

Figure 2. Simulated and measured above ground dry weight (means of 3 plots and the standard error) with different fertiliser-N treatments. Symbols • are experimental values; solid lines are simulated values with the original J-shaped model, dashed lines are from the modified S-shaped growth curve and modified *soil-N* model. The four solid lines for the N_{C240} treatment are simulated values at T_h = 61, 57, 50 and 42 (from the bottom to the top) respectively, where T_h represents harvesting date. The data set from N_C was used for calibration of the S-shaped growth curve and modification of *soil-N*, and the data sets from N_0, N_A and N_B were used for validation.

that growth rate is calculated by a differential equation

$$dW/dT = k_2 W G_f/(1 + W) \quad (1)$$

where k_2 is a crop dependent coefficient adjusted for daily temperature, and G_f ($\leq$ 1) is the ratio of %N in the plant to critical %N which is a correction coefficient to allow for any restriction in growth rate caused by sub-optimal %N in the crop (Greenwood & Draycott, 1989a). This equation is derived from the assumption that most vegetable crops in Europe are harvested long before any 'ceiling' yield is reached and the equation describes only the first and second phases of growth (Greenwood et al., 1977). In contrast, our measured W curves had inflection points at day 35 to 40 as the growth rate slowed towards the end of the experiment.

Growth curve calibration

In order to determine how well the model was able to predict dry weight production at different stages of growth, it was rerun assuming the plants were grown for T_h equal to 42, 50, 57 and 61 days with potential maximum dry weight (W_{MAX}) equal to 2.5, 3.0 3.5 and 4.3 t ha^{-1} at each of these T_h values respectively. The results for the N_{C240} treatment are shown in Figure 2d. When T_h = 42, simulated W was well fitted to measured W over the whole period of growth. By comparison, when T_h was set at 50, 57 or 61 days, the model increasingly underestimated W in the middle part of the curve, and the residual errors gradually increased. These results show that systematic errors in the model can be reduced by changing this one input parameter. N_ABLE can therefore only be used in the first three-quarters of the growing period. For prediction, we need to simulate the growth curve accurately throughout the whole growth period. An S-shaped curve was therefore calibrated by modifying the growth rate Equation (1) as:

$$dW/dT = k_2 W G_f G_k/(1 + W)\, G_k = (W_k/W)^n \quad (2)$$

where W_k is plant dry weight at day T_k ($T_k < T_h$), and n is a curvature coefficient.

Equation (2) was derived on the assumption that the growth rate *dW/dT* slowed for genetic or other reasons during the later part of the growth period even though soil temperatures were higher in July. There is evidence that growth rate *dW/dT* is a function of *W*, and that it changes from crop to crop, and from time to time (Evans, 1975; Hunt, 1982). For S-shaped curves, *dW/dT* was linearly related to *W* during the vegetative phase of the growth. *dW/dT* reached its maximum at the plateau in the middle of the time course, and it declined in the later phase of growth with the increase of *W* until the harvest (Hunt, 1982).

The relationship between *dW/dT* and *W* was examined by the field data from N_C plots. The modified *dW/dT* curve in Equation (2) was compared with $dW/dT = \mu\ W(1\text{-}W/W_{max})$ derived from a logistic equation (France & Thornley, 1984), where μ is a relative growth rate, and W_{max} is the final maximum dry weight. and it was also compared with field measured *dW/dT* calculated by $dW/dT = (W_i - W_{i-1}) / (T_i - T_{i-1})$, where i is the sample numbers 1 to 7. We found that Equation (2) gives a close simulation of the measured growth rate curve when $W > W_k$, while it gives a close simulation of $dW/dT = \mu\ W(1\text{-}W/W_{max})$ when $W < W_k$, where W_k= 2.58 at day T_k= 43 and n = 2 (i.e. $G_k = (2.58/W)^2$). With $G_k = (2.58/W)^2$, the model gives a good simulation of the measured S-shaped growth curve (e.g. dashed line of Figure 2d). Further validation of the growth curve (calculated using the same parameters) has been made for the other treatments and the modified curves for the N_0, N_A and N_B treatments are shown in Figure 2a, 2b, 2c.

Soil mineral N curve calibration

When the S-shaped growth curve was used, it was found that the simulated *soil-N* in the 0–30 cm layer was much lower than that using a J-shaped growth curve. The lower values of *soil-N* were influenced by the larger dry weights found using the S-shaped growth curve, but the main effects were due to the use of the Equation:

$$REC = min(REC_0 - 0.517(G_f - 0.71), 0.90) \quad REC_0 > 0.65 \qquad (3)$$

where REC_0 is the input parameter of *REC* listed in Table 2, and G_f, in most cases, equals to 1 in higher N plots. FORTRAN code inspection of N_ABLE proved that Equation (3) worked for lettuce only when $REC_0 > 0.65$. Equation (3) was used to simulate the effect that *REC* tended to decrease with increase in %N in the plant (see Equation 9 in Greenwood & Draycott (1989a)). Our sensitivity analysis found that *soil-N* declined unusually when $REC_0 > 0.65$ at higher N plots. For example, simulated *soil-N* = 149 kg ha^{-1} at REC_0 = 0.65, but *soil-N* = 102 kg ha^{-1} at REC_0 = 0.66 in one of our lettuce experiments because *REC* was recalculated by Equation (3) as $REC = 0.66 - 0.517 (G_f - 0.71) = 0.51$, where $G_f = 1$.

In order to eliminate this effect, the simulation was run again with the modification of Equation (3) that $REC = REC_0$ irrespective of the G_f value, and it was found that simulated *soil-N* was increased by about 55 kg ha^{-1} at higher levels of N and simulated *W* was increased by 0.16-0.20 t ha^{-1} at lower levels of N. Therefore, the values of *W* in Figure 2 simulated using only the S-shaped curve correction were updated with values of *W* simulated with the $REC = REC_0$ correction. The simulated *soil-N* with and without both the S-shaped curve and $REC = REC_0$ corrections are shown in Figure 3.

Soil mineral N evaluation

Comparison of simulated and measured *soil-N* in the 0–30 cm layer (Figure 3) shows that the simulated *soil-N* corresponds well to measured values during the whole growth period. The simulated *soil-N* data with the S-shaped growth curve and $REC = REC_0$ corrections are lower than those with a J-shaped growth curve in the middle of the growth period, but the reverse is true in the later of the growth period. The standard error of the mean of the measured data was

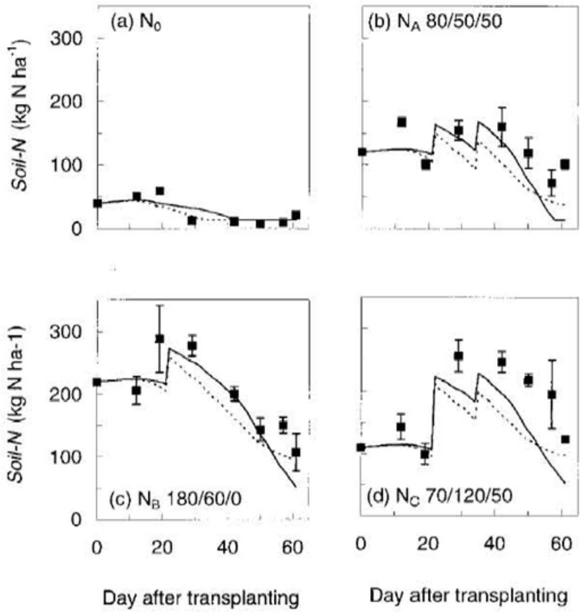

Figure 3. Simulated and measured soil mineral N in the 0–30 cm layer (means of 3 plots and the standard error) for different N treatments. Symbols ■ are experimental values; absence of a standard error bar means that it is within the symbol size. Solid lines are simulated values with the original J-shaped model, dashed lines are from the modified S-shaped growth curve and modified *soil-N* model.

larger than that for dry weight at higher levels of N, much as has been observed by Jackson et al. (1994). This is possibly because N fertiliser was not evenly applied in the plots or not well distributed in soil when the samples were taken. At the final harvest, simulated *soil-N* values were lower than measured, indicating that the model over-predicts N uptake or nitrate leaching or under-predicts nitrogen mineralisation rate close to harvest. For treatments N_A, N_B and N_C, there were no significant differences for measured dry weight (Figure 2), but the measured soil mineral N was different during the growing period (Figure 3). Maximum values of *soil-N* for the three treatments were just under 200 kg N ha^{-1} in N_A, 300 in N_B and 250 in N_C which indicates that N_A has the least N-leaching potential in this study.

Statistical evaluation

Figures 2 and 3 give a visual impression of the improvement of fit by the S-shaped growth curve. Figure 2 indicates that the residual error of *W* can be minimised for the entire growth period by using the S-shaped growth model (Equation 2). These figures do not indicate the degree of improvement or how far the discrepancies can be attributed to experimental error. In order to achieve this objective, a regression analysis with a lack of fit test was carried out for the S-shaped growth equation for each of the six treatments. This examined the extent to which the sums of squares of residual errors can be attributed to experimental error. The analysis was followed by partitioning the sums of squares of residuals (SS_R) into two parts, the sums of squares of randomised error (SS_E) and the sums of squares of lack of fit (SS_{LF}). The degree of freedom of residuals (DF_R) can then be partitioned into two parts, the degree of freedom of randomised error (DF_E) and the degree of freedom of lack of fit (DF_{LF}). Details are given by Whitmore (1991). In brief, if there are n measurements each with r replicates in each experiment and the regression model is $y = x$ (y is measured values; x simulated values), then:

$$\begin{aligned} SS_R &= SS_E + SS_{LF} \quad (4)\\ DF_R &= DF_E + DF_{LF}\\ SS_R &= \sum\sum(y_{ij} - x_i)^2\\ DF_R &= nr\\ SS_E &= \sum\sum(y_{ij} - \bar{y}_j)^2\\ DF_E &= n(r-1)\\ SS_{LF} &= SS_R - SS_E\\ DF_{LF} &= n \end{aligned}$$

where y_{ij} are measured values for the ith measurement in the jth replicate, x_i are simulated values for the ith measurement and $\bar{y}_j$ the measured mean in the ith measurement. The variance ratio is:

$$F_{LF} = (SS_{LF}/DF_{LF})/(SS_E/DF_E) \quad (5)$$

Statistical inferences from the above analysis of variance of residuals can be drawn as follows. If $F_{LF} < F_\alpha$ (DF_{LF}, DF_E), where α is the significant level of F values, i.e. $\alpha = 0.05$ or 0.01 *etc*., then (1) the lack of fit error is small and the simulation is accurate, or (2) the lack of fit is large, but the experimental error is also large. If $F_{LF} \geq F_\alpha$ (DF_{LF}, DF_E), then the lack of fit error is significantly different from the experimental error and there are three possible reasons: (1) the experiment was very accurate, e.g. $SS_E \approx 0$, but actual lack of fit error is small, (2) the experimental error is reasonable, the model removes much of the variance (e.g. 95%) but F_{LF} is just larger than its F_α, i.e. $\alpha = 0.05$ or (3) the experimental error is reasonable, but the lack of fit error is quite large. It is clear that only in case (3) can we conclude that the model gives poor prediction, and reasons behind the lack of fit should be identified.

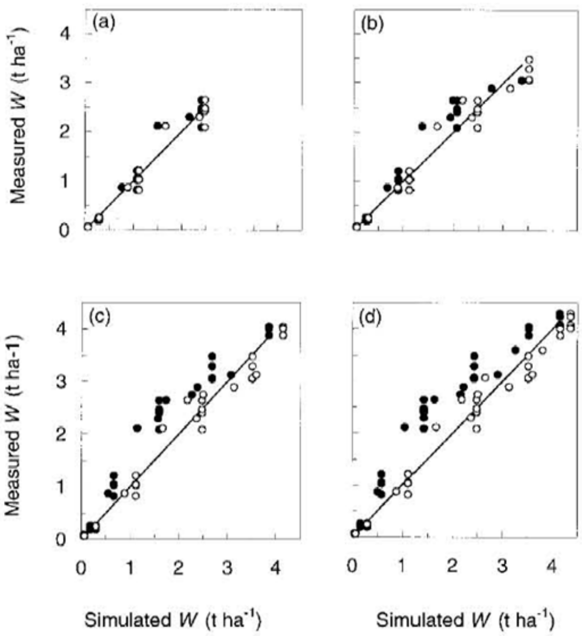

Figure 4. Comparison of measured dry weight (means of 3 plots) against simulated values at different harvest times through the 6 N treatments listed in Table 3. Symbol • represents comparisons made using the original J-shaped growth curve model, and symbol o represents comparisons made using the modified S-shaped growth curve and modified *soil-N* model; lines are $y = x$. (a) $T_h = 42$, (b) $T_h = 50$, (c) $T_h = 57$, (d) $T_h = 61$.

Following the above method, the lack of fit test for each treatment was analysed by SAS software, using the modified model with the S-shaped growth curve and $REC = REC_0$ correction assuming T_h varied between 42 and 61 days, as above. The F_{LF} values calculated by Equation (5) are listed in Table 3, and graphical comparisons with the lines of perfect fit of measured W and *soil-N* against simulated values for all treatments are shown in Figures 4 and 5.

A clear statistical conclusion can be drawn from the values in Table 3. All F_{LF} values for the S-shaped growth model were not significant at the 0.05 level except for the N_0 and N_B treatments, indicating that the residual errors in treatments N_{50}, N_A, N_C and N_{310} are all from experimental error irrespective of T_h values. This proved that the modified growth equation gave a good description for all fertiliser N-applied plots except N_0 and N_B plots. In contrast, significant F_{LF} values in N_0 and N_B treatment plots indicate a lack of fit error which is significantly different from experimental error. The significant F_{LF}

Table 3. The lack of fit test on residuals between simulated and measured dry weight for the model $y = x$. where y is measured dry weight for each treatment (3 replicates), and x is simulated dry weight by N_ABLE with the modified S-shaped growth curve and modified *soil-N* equations. Regression was carried out by SAS

Treatment	$F_{LF}(T_h$=42)	$F_{LF}(T_h$=50)	$F_{LF}(T_h$=57)	F_{LF} (T_h=61)
N_0	4.74*	4.7*	4.39*	4.98* *
N_{50}	0.51	0.68	1.3	1.44
N_{A180}	2.02	0.63	1.73	1.67
N_{B240}	16.24* *	4.25*	3.96*	3.38*
N_{C240}	0.23	0.26	0.35	0.42
N_{310}	0.28	0.38	0.43	0.69

* and * * refer to F_{LF} significant at 0.05 & 0.01 levels.

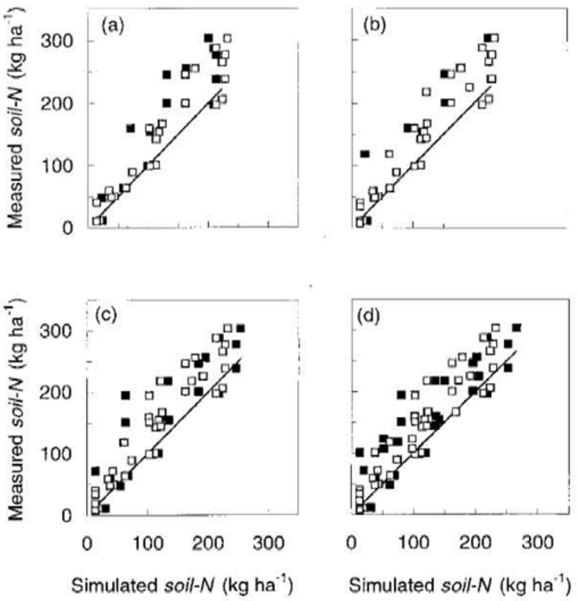

Figure 5. Comparison of measured soil mineral N (means of 3 plots) against simulated values at different harvest times through the 6 N treatments listed in Table 3. Symbol ■ represents comparisons made using the original J-shaped growth curve model, and symbol □ represents comparisons made using the modified S-shaped growth curve and modified *soil-N* model; lines are $y = x$. (a) T_h = 42, (b) T_h = 50, (c) T_h = 57, (d) T_h = 61.

values in N_B resulted from lower dry weight caused by higher basal dressing amounts of N fertiliser which is harmful to root growth in the early stage of lettuce seedling growth or caused by a lower experimental error. The reason why the model underestimates dry weights at N_0 plots needs to be investigated. However, there was little difference between the measured and simulated *soil-N* when T_h was changed, and both the J-shaped and S-shaped growth model underestimated *soil-N* irrespective of growth period (Figure 5).

Conclusions

The measured dry weight growth curve of lettuce can be described as an S-shaped or a J-shaped curve depending on the date of period of growth. However the N_ABLE model predicts that the dry weight curves always follow a J-shaped curve in summer season. As a result, the model only describes the exponential part of the growth curve accurately and should not be used beyond that point. For longer periods of growth, a modified growth equation has been developed based on an asymmetrical S-shaped curve: $dW/dT = k_2W\ G_fG_k\ /\ (1+W)$, where $G_k = (2.58\ /W)^2$. Using this equation, yield forecasting became more accurate at all stages of growth for this data set. However, this modified growth equation needs to be validated against further data sets, and there is a need to establish why this model underestimates dry weights with low N inputs.

Curves of response of dry weight to N fertiliser input are different for the measured and simulated data. The model predicts a diminishing return curve with the same final W for N $\geq$ 180 kg ha^{-1} (Figure 1b), while the measured W response curve included yield depression when N $\geq$ 250 kg/ha (Figure 1a). This result is similar to those of Sorensen et al. (1994) and Soundy & Smith (1992). Using the un-modified growth curve, the residual difference between simulated and measured W will be higher at high N levels and the model should be adjusted to allow for this effect of nitrogen on yield.

Simulated soil mineral N in the 0–30 cm layer was significantly lower than measured values using default parameters, but this was improved by changing the parameters for the apparent recovery of soil mineral nitrogen to 0.70 and mineralization rate of soil organic

N to 0.86 kg N ha^{-1} d^{-1} for all treatments, these values being derived from field data. This means that soil mineral N is particularly sensitive to *REC* and *NR* and further information about their variability in field experiments is necessary. *Soil-N* was also improved by modifying Equation (3) by $REC = REC_0$ irrespective of the G_f value, but the effect of Equation (3) on *soil-N* in other crops should be examined in future. The measured experimental errors for soil N are larger than for dry weight at higher levels of N input and this larger error may result in lower F_{LF} values. Therefore, care should be taken when carrying out regression analysis with a lack of fit test for *soil-N*. We suggest that the time of soil sampling should not be near the time of top dressing with N fertiliser in any future experiment.

The lack of fit test is a useful method to distinguish experimental error from residual error provided replicates are available, but the F_{LF} value is more sensitive to the magnitude of SS_E and DF_E, so stability of the F_{LF} values in further tests might be compared by other goodness of fit tests, such as the *student-t* statistic.

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3.4 Personal Case Study Farm (Assignment D)

- Collect the required resource and production data from a farm of your choice.
- Obtain details on fertiliser and effluent application guidelines for your region.
- Use Overseer to prepare a nutrient budget for the farm.

For pastoral farms use a similar nutrient management plan report format provided for Assignment A. For arable farms use a similar nutrient management plan report format provided for Assignment B.

Further instructions for this nutrient management report will be sent to you via email.