SPTS No. 17238

Nutrient management for vegetable crops in NZ – recommendations and supporting information

Edition 1.0, January 2019

JB Reid, BP Searle, A Hunt, PR Johnstone
Plant & Food Research, Hawke's Bay

Jeff Morton
MortonAg, Napier

A Plant & Food Research – Internal Report

Nutrient management for vegetable crops in NZ – recommendations and supporting information
Edition 1.0, January 2019

JB Reid, BP Searle, A Hunt, PR Johnstone
Plant & Food Research, Hawke's Bay
Jeff Morton
MortonAg, Napier

DISCLAIMER

Unless agreed otherwise, The New Zealand Institute for Plant & Food Research Limited does not give any prediction, warranty or assurance in relation to the accuracy of or fitness for any particular use or application of, any information or scientific or other result contained in this report. Neither Plant & Food Research nor any of its employees shall be liable for any cost (including legal costs), claim, liability, loss, damage, injury or the like, which may be suffered or incurred as a direct or indirect result of the reliance by any person on any information contained in this report.

LIMITED PROTECTION

PUBLICATION DATA

Reid J, Searle B, Hunt A, Johnstone PR, Morton J. December 2018. Nutrient management for vegetable crops in NZ – recommendations and supporting information, Edition 1.0, January 2019. A Plant & Food Research internal report. Milestone No. 79795. Contract No. NA. Job code: P/442060/23. SPTS No. 17238. DOI 10.5281/zenodo.2401444

Report approved by:

Jeff Reid
Principal Scientist, Field Crops
December 2018

Warrick Nelson
Operations Manager, Sustainable Production
December 2018

For further information please contact:

Jeff Reid
Plant & Food Research Hawke's Bay
Private Bag 1401
Havelock North 4157
NEW ZEALAND
Tel: +64 6 975 8880
DDI: 6 975 8897
Fax: +64 6 975 8881
Email: Jeff.Reid@plantandfood.co.nz

Publication date 01/2019
Published by
New Zealand Institute for Plant & Food Research Limited
Private Bag 1401, Havelock North 4157, New Zealand

Printed Book: ISBN 978-0-473-46754-8
pdf version: ISBN 978-0-473-46755-5

DOI: 10.5281/zenodo.2401444

Abbreviations and symbols commonly used in this book

ASC	Anion storage capacity (% P retention)
Ca	Calcium
CEC	Cation exchange capacity
Cl	Chlorine
DAP	Di-ammonium phosphate
DM	Dry matter (of plants)
K	Potassium
MAF	Ministry of Agriculture and Fisheries
Mg	Magnesium
MOP	Muriate of potash, KCl
N	Nitrogen
Na	Sodium
NH_3	Ammonia
NH_4^+	Ammonium
NMP	Nutrient management plan
NO_3^-	Nitrate
P	Phosphorus
ρ_{field}	dry bulk density of the top 15 cm of soil in the field at planting
ρ_{lab}	bulk density or "volume weight" of air-dry sieved soil in the laboratory as sampled for chemical analysis
QT	Quick test
S	Sulfur
SOA	Sulfate of ammonia NH_4SO_4
SOP	Sulfate of potash, K_2SO_4
TBK	Tetraphenyl Boron K – also called Reserve K

Table of Contents

1 Introduction 1
  1.1. Crop needs for mineral nutrients 1
  1.2. Nutrient supply from the soil 4
  1.3. Nutrient supply from fertilisers and composts 7
  1.4. Code of Practice for Nutrient Management 10
  1.5. Nutrient Management Plans & Nutrient Budgeting 11
2 Making nutrient recommendations 13
  2.1. Nutrients to grow the crop 13
  2.2. Maintenance nutrient applications 17
  2.3. Nutrient recommendations for crops not in this book 17
  2.4. From recommendation to application rates 18
  2.5. A final note 18
3 Beans for processing 19
  3.1. Potential yields 19
  3.2. Nutrients to grow the crop 19
  3.3. Maintenance nutrient applications 21
  3.4. Plant nutrient analysis 21
4 Buttercup squash 22
  4.1. Potential and marketable yields 22
  4.2. Nutrients to grow the crop 22
  4.3. Maintenance nutrient applications 26
  4.4. Plant analysis 26
  4.5. Other cucurbits 27
5 Cabbage, broccoli and cauliflower 28
  5.1. Potential, field, and marketable yields 28
  5.2. Nutrients to grow the crop 29
  5.3. Maintenance nutrient applications 33
  5.4. Plant analysis 33
6 Carrots 36
  6.1. Potential yields 36
  6.2. Nutrients to grow the crop 37
  6.3. Maintenance nutrient applications 39
  6.4. Plant analysis 40
7 Lettuce 42
  7.1. Potential and field yields 42

7.2. Nutrients to grow the crop 43
7.3. Maintenance nutrient applications 47
7.4. Plant analysis 47
8 Onions 50
8.1. Potential, field, and marketable yields 50
8.2. Nutrients to grow the crop 51
8.3. Maintenance nutrient applications 54
8.4. Plant analysis 54
9 Peas for processing 56
9.1. Potential yields 56
9.2. Nutrient recommendations 56
9.3. Plant analysis 57
10 Potatoes 58
10.1. Potential, field, and marketable yields 58
10.2. Nutrients to grow the crop 59
10.3. Maintenance nutrient applications 63
10.4. Plant nutrient analysis 64
11 Spinach, silverbeet and beetroot 66
11.1. Potential, field, and marketable yields 66
11.2. Nutrients to grow the crop 67
11.3. Maintenance nutrient applications 69
11.4. Plant analysis 70
12 Sweet corn 72
12.1. Potential yields 72
12.2. Nutrients to grow the crop 73
12.3. Maintenance nutrient applications 75
13 Tomatoes for processing 78
13.1. Potential and field yields 78
13.2. Nutrients to grow the crop 79
13.3. Maintenance nutrient applications 82
13.4. Plant analysis 83
14 Acknowledgements 84
15 References 85

1 Introduction

This publication is a resource of further detail for the 2018 book **Nutrient Recommendations for Vegetable Crops in NZ** (Reid & Morton 2018).

Vegetables are a key part of the human diet and they earn New Zealand valuable export dollars. Only about 5% of the country's soils are suitable for intensive horticulture so it is important that optimal, sustainable yields are obtained. Vegetable crops can remove large quantities of plant nutrients from the soil that need to be replaced in sustainable production systems. However, if more nutrients are applied than required for replacement, soil nutrients can become excessive. This can reduce crop yields and quality, and increase the risk of damage to the wider environment. The importance of making the best decisions for nutrient management goes far beyond the $ costs of fertiliser products.

In 1986, MAF published *Fertiliser Recommendations for Horticultural Crops*. The book summarised nutrient requirements for the major vegetable crops based on research results obtained up until then (Wood et al. 1986). In 2000, the Vegetable Growers Handbook (Wallace 2000) contained information for fertiliser use, but the scientific basis for the recommendations was unclear. Since then, much has changed in the business, social and regulatory environment of horticulture. Crop location, varieties, management practices and yield expectations have changed, and growers are more aware of the impact of their practices on the wider environment. New scientific approaches have enabled researchers to quantify the influences of many of the key interactions between plants, soils, and management that influence productivity, profitability and risk.

The 2018 book built on the knowledge succinctly summarised in the 1986 book with the results of a further 32 years of research. *It is the role of this publication to provide supporting details and references.*

Key Point: Getting started

It is important to read the generic material in Chapters 1 and 2 *before looking for recommendations for specific crops*. It is particularly important to read section 1.1 *Crop needs for mineral nutrients.* The terms defined there for crop yield may be new to some readers and are used extensively through the book.

The recommendations here are based on the best current experimental evidence, but they are not prescriptive for every crop situation. At times it may be beneficial to use the skills of a nutrient management adviser to interpret and if necessary modify them.

1.1. Crop needs for mineral nutrients

Plant tissue consists of carbon (C), hydrogen (H), oxygen (O), and about 14 other essential elements (Marschner 1995). The first three (C, H, O) are obtained from the air or water and make up most of the organic compounds in plants. The remainder are often called major and minor (or trace) mineral nutrients depending on how much plants typically require. They are:

Major elements – nitrogen (N), phosphorus (P), potassium (K), sulfur (S), calcium (Ca), and magnesium (Mg);

Minor (trace) elements – boron (B), chlorine (Cl), copper (Cu), iron (Fe), manganese (Mn), molybdenum (Mo), and zinc (Zn).

All these are taken up from the soil solution in the ionic form. When supply of any one nutrient is low it will limit crop growth and yield, but the limitation becomes less and less as more of the nutrient is supplied. It may even reach the point where adding any more will decrease growth and yield (see *Economic matters* below). If any single nutrient is limiting growth it will reduce the responsiveness of the crop to additions of the other nutrients.

Potential, field and marketable yields

Nutrient uptake and yield are mutually dependent. The amount of each nutrient that a crop needs to achieve its maximum yield and quality depends primarily on its potential yield.

Wherever possible, for each crop we start by considering the potential yield. Other types of yield are referred to in this book: *field*, *harvested*, and *marketable yields* are all less than the potential yield. The meanings of these terms are explained by the sequence in Figure 1-1.

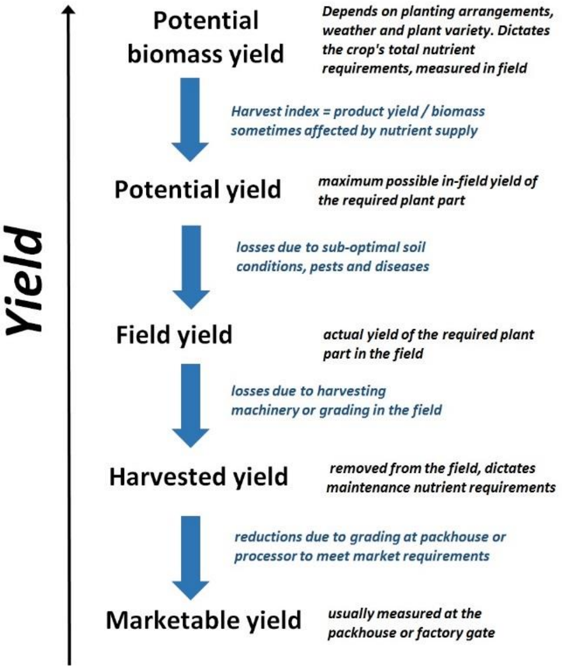


Figure 1-1. Relationships between potential, field and marketable yields in vegetable crops.

As noted above, potential yield sets the top limit for the crop's nutrient uptake requirements. But the field yield may be less because of stresses due to water availability, pests or diseases.

Usually these stresses reduce the amount of nutrients that the crop will need, *and you cannot compensate for these yield losses by applying more fertiliser*. The best example of this is water stress. Water stress during growth will reduce the yield and the nutrient requirements proportionally.

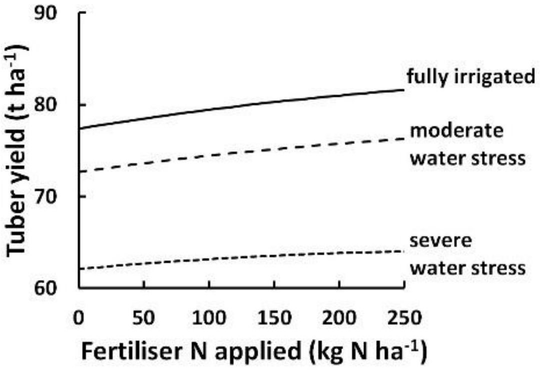


Figure 1-2. Effect of water stress (0, 2 and 4 weeks of missed irrigation) on the response of potatoes to N fertiliser under Canterbury conditions. The results are simulated using the Potato Calculator and PARJIB (Jamieson et al. 2004; Reid et al. 2011)The soil contained 100 kg/ha of Available-N. There were no significant shortages of other nutrients.

Target yield. Sometimes growers will need to calculate nutrient requirements to achieve a *target yield* that they want from the crop. The value may be based on previous experience of the crop and land, or by marketing requirements, but it should never be set greater than the potential yields indicated in each chapter. Achieving a field yield close to the potential value requires more than optimum supply of nutrients – it requires also excellent soil physical conditions, control of pests and diseases, and a perfectly timed harvest.

Plant nutrient concentrations and nutrient uptake

The concentrations of most of the major nutrients are greatest when the plants are young. As the plants get larger more and more of the plant mass is made up of structural material like stems that is mainly complex carbohydrates with few mineral nutrients. The growth of this structural material “dilutes” the concentrations of nutrients like N, P and K especially, which fall as the crop gets older and bigger (see for example Figure 1-3). Set against this, as the plants get bigger their root systems can take up more and more nutrients (Figure 1-4), and nutrient uptake rates usually peak when the crop is growing most quickly. Some crops, like onions and sweet corn, are quite good at regulating this uptake so they don’t take up more nutrients than they need for maximum growth. Some others, like carrots and spinach, regulate this uptake quite weakly. The net result for almost all crops though is that the concentrations of the major nutrients decrease as the plants grow.

Often we want to know the least amount of nutrient that the crop must take up while still achieving its maximum growth rates. These critical nutrient concentrations also decrease as the plants get bigger and they are difficult to measure in field crops. This makes it difficult to interpret measured concentrations of leaf, shoot or whole plant nutrient concentrations. Overseas, some N fertiliser recommendations are based entirely on such *critical nutrient dilution curves* (Defra 2010). That is not always possible here because of the lack of New Zealand relevant data, the sizable statistical uncertainties associated with some of the overseas data, and the considerable complications that arise when comparing crops grown at different population densities.

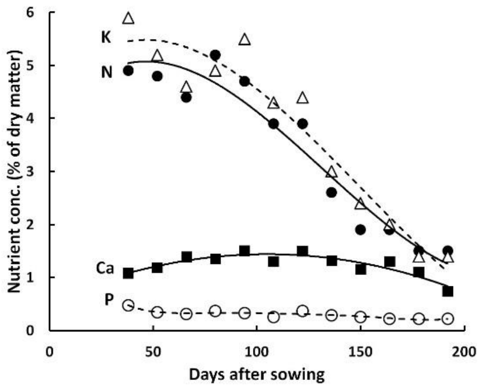
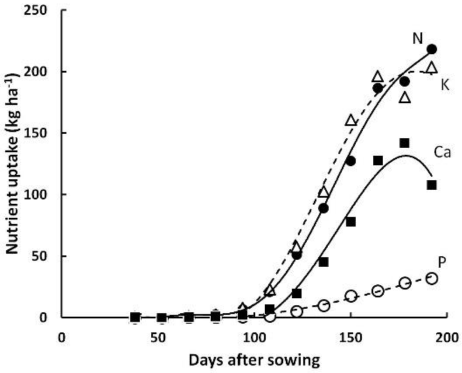


Figure 1-3. Nutrient concentrations in leaves and bulbs of an onion crop (‘Pukekohe Long Keeper’) grown at Pukekohe in 1993–94. Drawn from data kindly supplied by Sher (1996b). Note that Ca concentrations did not follow the same pattern as the other nutrients. This crop appeared to be adequately supplied with nutrients.

Figure 1-4. Nutrient uptake by an onion crop grown at Pukekohe. This is the same crop as Figure 1-3. Redrawn from data kindly supplied by David Sher. The decline of Ca content of the crop probably reflected loss of the older leaves late in the season.



Nutrient uptake vs nutrient supply

Crops take up most of their mineral nutrients from the soil. Only a fraction of the total amount of nutrients held in soil is rapidly available to plants. Vegetable crops typically have a short growing season and need to take up large quantities of nutrients quickly. Their root systems are quite sparse, and do not have enough time to fully explore the soil and access nutrients in it.

So, compared with pasture species, arable crops and perennial horticultural crops, most vegetable crops require the soil to have quite high concentrations of mineral nutrients so that they can yield to their potential.

Having said that, it is easy to over-estimate the amount of nutrients that need to be added to a soil for optimum vegetable growth. Some vegetables can take up nutrients well beyond the amounts they actually need (this is called *luxury uptake*). Leafy vegetables and root crops are predisposed to luxury uptake (especially of N and K), and this may be associated with negative effects on crop quality. Furthermore, yield of some crops can be decreased by an over-supply of some nutrients (examples include N for tomatoes and P for lettuce).

1.2. Nutrient supply from the soil

Vegetable growing soils in New Zealand

The bulk of the vegetable industry is based around several specific areas where soils and climate are suitable, although some crops are also grown in market gardens around most cities and towns. The major growing areas are Canterbury in the South Island and Hawke's Bay, Gisborne and the Waikato in the North Island (Aitken & Hewett 2016).

Soils of sedimentary origin

Many areas growing vegetable crops are based on young sedimentary soils formed by river systems. Usually these are Recent soils (Hewitt 2010). Examples include the Mataura soils in Southland, Templeton soils in Canterbury, Twyford soils around Hastings and Matawai soils around Gisborne. Natural drainage is usually good, or artificial drainage has been installed. Soil organic matter concentrations are medium to high (3–5% organic-C) when cultivated from pasture but are often depleted under continual cropping. Most Recent soils have low anion storage capacity (10–20%), medium cation exchange capacity or CEC (15–20 meq/100 g) and medium to high reserves of potassium, magnesium and calcium (Hewitt 2010).

Soils of volcanic origin

These are usually well drained. Examples include Granular soils (such as Patumahoe soils around Pukekohe, and Wairereka soils near Oamaru), Allophanic soils (such as Ohakune soils around Ohakune) and Allophanic Brown soils (such as Levin soils in Horowhenua) (Hewitt 2010). Soil organic matter concentrations are higher than in sedimentary soils and are slower to deplete with continual cropping. In contrast to sedimentary soils they have high anion storage capacity (70–90%) and CEC (25–30 meq/100 g) but often have low reserves of potassium (Hewitt 2010; Kirkman et al. 1994).

Soils of organic origin

For horticultural production these soils normally need artificial drainage installed. The ones used for vegetable cropping are mainly located in Waikato (e.g. Kaipaki soils) and Southland (e.g. Otautau soils). Soil organic-C concentrations are high (15–40%). Anion storage capacities can be moderately high (40–60%) if the mineral soil content is of volcanic origin but lower if it is of sedimentary origin. CEC is high (>40 meq/100 g), which means that they can retain potassium, magnesium and calcium (Hewitt 2010; Kirkman et al. 1994).

Assessing soil nutrient status

This is a crucial step in managing nutrients for vegetable crops, and for each crop soil testing should be carried out before deciding a fertiliser regime. For some crops, this can be complemented by plant analysis at specific growth stages.

There is a wide range of soil tests available from most commercial laboratories. The traditional analyses for readily available soil nutrients include:

- Olsen P – a measure of plant-available P
- Quick test (QT) Ca, Mg, K and Na – measures of the plant-available amounts of these nutrients
- CEC – a measure of the capacity of a soil to store positively charged nutrients such as Ca, Mg, and K
- pH – a measure of soil acidity and an indication of both lime requirement and the likelihood of trace element deficiencies or toxicities.

The usual analyses now often include:

- Tetraphenyl Boron K (TBK) – a measure of the K reserve
- Organic-C – a measure of the organic matter content of the soil
- Anion storage capacity (previously called *phosphate retention*) – measures the capacity to store P and S

Key point: Soils that fix P

Growers sometimes expect the optimum soil test P to be greater on volcanic soils or other soils with a high anion storage capacity (ASC, or P retention %). *There is no good evidence for this in vegetables* – the standard soil test ranks P supply very well across a wide range of soil types (Edmeades et al. 2006).

But high ASC values *do* restrict the efficiency of P fertilisers – so band soluble P fertiliser as much as possible. This reduces the percentage that is fixed onto soil surfaces.

We recommend that growers request that their soil test reports include results for the "volume weight" or "bulk density" of the soil as tested in the laboratory. This is because most laboratories measure soil concentrations of the major nutrients on a volume basis (for example µg of P /ml of soil), but measures on a mass basis are very useful when making nutrient recommendations. Furthermore, overseas and New Zealand laboratories often differ considerably in the units they use to report soil test results. Table 1-1 provides some conversion factors for commonly used units. The bulk density features prominently in these conversions.

Table 1-1. Converting New Zealand Quicktest results into other units, adapted from Cornforth and Sinclair (1984). It is important that your laboratory results include the "volume weight" or "bulk density" of the soil as tested in the laboratory (not the field); here we give it the symbol ρ and it has units of g/mL.

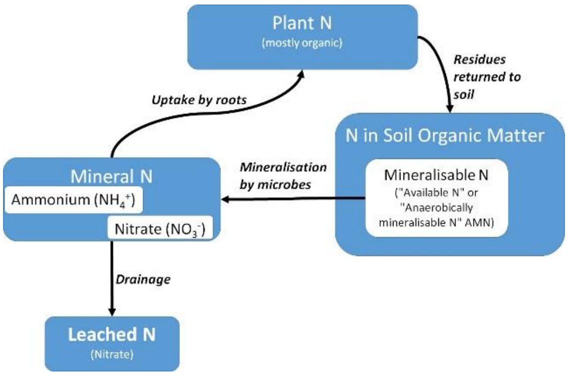
Reporting unit	Ca	K	Mg	Na	P	S
me/100g	Ca x 0.57 /ρ	K x 0.046 /ρ	Mg x 0.038 /ρ	Na x 0.020 /ρ	–	–
mmols/kg	Ca x 2.8 /ρ	K x 0.23 /ρ	Mg x 0.19 /ρ	Na x 0.10 /ρ	P x 0.032 / ρ	S x 0.0331
µg/g or mg/kg	Ca x 0.071 /ρ	K x 0.0059 /ρ	Mg x 0.0079 /ρ	Na x 0.0044 /ρ	P /ρ	S x 1

Soil analysis is often unreliable for measuring trace-element availability, because solubility of these nutrients varies greatly with changes in soil pH and aeration status. They are best measured by plant analysis.

Soil nitrogen tests

Measuring soil N is now essential for economic and environmental reasons. This is a major change from the 1986 recommendations. However, the total amount of N and the amount of organic N in the soil are relatively poor indicators of what plants can access.

There are various soil tests available. It is important to understand what each test tells you so you order the correct test. The recommendations in this book, and a number of crop calculators, use measures that are usually called *Mineral-N* and *Available-N*.



Mineral-N

Also called *Deep Soil Mineral N*, this measures the nitrate and ammonium content of freshly collected soil. It represents the N *immediately* available to plants and does not account for what may be mineralised from soil organic matter over the coming weeks and months. Sampling depths often go from the surface to 60 cm. In each paddock, take about 8–12 randomly located samples, but keep away from headlands, gates, and stock camps.

The results are reported for ammonium-N *and* nitrate-N, in units of µg/mL, µg/g or mg/kg (the numbers are identical for all those units). To convert these to kg N/ha you multiply them by sampling depth and the soil bulk density.

$$
\begin{aligned}
kg\ N/ha = {} & (ammonium\text{-}N + nitrate\text{-}N\ \mu g/g) \\
& x\ depth\ of\ soil\ sample\ (cm) \\
& x\ relevant\ bulk\ density\ (g/cm^3) \\
& x\ 0.1
\end{aligned}
$$

The 0.1 factor in this equation balances the units from $\mu g/cm^2$ to kg/ha. Typical values for the bulk density would be 1.1 g/cm^3 for the top 0–30 cm and 1.3 for the 30–60 cm depths. If the samples were taken from 0–60 cm in one core, use 1.2 g/cm^3. For example, if nitrate was 11.9 µg/g and ammonium was 6.0 µg/g, the total Mineral-N would be:

$$(11.9 + 6.0\ \mu g/g)\ x\ 60\ cm\ x\ 1.2\ g/cm^3\ x\ 0.1 = 129\ kg\ N/ha$$

In sedimentary soils the bulk density is usually greater in the subsoil than the topsoil. Subsoil values may be close to 1.5 g/cm^3 (rising to 1.6–1.7 g/cm^3 if there is an appreciable compaction pan).

Key point: Keep the samples cool

For both Mineral-N and Available-N measurements the soil samples must be chilled or frozen to prevent mineralisation occurring in the sample while in transit to the laboratory. Samples must arrive at the laboratory at less than 4°C.

Available-N, also known as Anaerobic Mineralisable Nitrogen (AMN)

This is a measure of N mineralised under specific laboratory conditions (anaerobic incubation at 40°C for 7 days). It represents an estimate of nitrogen that will be *potentially* mineralised in the field through the season. It does not include the immediately plant-available component of soil nitrogen (Mineral-N). Usually, Available-N is measured only in the top 15 cm of soil as this is where the organic matter is most concentrated. *The results are reported as kg N/ha.*

For more information see Francis and Curtin (2002) and Curtin et al. (2017).

Soil sampling

This should be carried out well before planting. Take samples from 0–15 cm depth (deeper for soil mineral-N, see below). The best benefit is achieved by regular testing over a number of years.

Setting up a soil monitoring system on your farm

- Identify different soil types in each paddock.
- Sample each paddock before every crop. The cost of this is regained by savings on fertiliser and improved yield.
- Across or along each paddock, set up and mark a transect across each of the major soil types. The idea is that you will return to this transect to take soil samples before each crop. Or you could use 15–20 GPS waypoints and take cores from the same spots whenever the paddock is sampled.
- Along the transect take 15–20 cores at equal intervals, or take samples from each of your GPS waypoints.
- Combine and mix the samples from the major soil types in each paddock. Then conduct soil tests according to the recommendations for each crop (see specific chapters). Usually this involves soil pH, P, K, Mg, Ca, CEC, and Available-N or Mineral-N. Every 4–5 years, analyse for organic-C.
- Where possible, take the samples in the same month of each year (when there is the most constant moisture status).

Using the monitoring results

- For the next crop plan the nutrient management according to the specific recommendations given in this book.
- Plot the trends in soil test values over time. Use these trends (over at least four sampling occasions) to assess whether fertiliser nutrient application has been sufficient or inadequate to maintain soil fertility.
- *If a soil test value has been climbing*, check why. In particular check if previous applications have been above recommended rates. Make appropriate corrections to your future fertiliser application rates.
- *If a soil test value has been falling*, identify if that matters by comparing values with the soil test ranges referred to in the crop chapters. It may be that you should increase the size of the maintenance applications. Remember that in some cases a reduction in soil test values may be desirable if the initial values are excessive.
- Plot trends in organic-C concentrations over time to assess what effect your management is having on soil nutrient reserves. Soil organic matter (as indicated by organic-C) should be maintained or increased by including grazed pasture in the rotation. Cultivation practices may need to be reviewed if soil organic-C shows a downward trend.

1.3. Nutrient supply from fertilisers and composts

The chapters for each crop here emphasise the best amounts of nutrients to apply, the most appropriate placement of fertilisers, and the timing of applications so the crop has the best opportunity to take up the nutrient supplied.

Key point: The 4 Rs

The principles of best practice with fertiliser applications are neatly summarised in the 4 Rs: Right product; Right rate; Right place; Right time (and see also the section Code of Practice for Nutrient Management).

The best outcomes may require multiple small applications rather than a single large application. The choice of which fertiliser product is down to the grower or adviser.

Forms of fertilisers

Solid fertilisers are used as either dry mixed blends of powders or granules.

Granular fertilisers are most frequently used for vegetable crops. The most common products in New Zealand are urea, DAP and SOA. They are made by finely grinding the ingredients and forming them into roughly spherical granules (4–5 mm diameter). These are dried and hardened. Granule size needs to be as even as possible so they flow freely through the fertiliser box on the drill when used as a starter fertiliser.

Compound fertilisers are made from combining different chemical compounds into granules. In some products, not all the granules contain all the ingredients. Examples where all ingredients are in each granule include Nitrophoska® and Yara Mila® Complex™ (these products contain ammonium nitrate, SOA, SOP or MOP, and a range of phosphate compounds).

Blended fertilisers are dry mixes of different solid fertilisers. There may be a large variation in granule size, and compared with compound fertilisers the blends may not be as stable during storage and handling.

In **controlled-release fertilisers and some slow-release fertiliser** the granules are coated with a polymer. Compound fertiliser examples include Osmocote® and Agroblen® and single-compound examples include urea in Smartfert®. The polymer slows the nutrient release into the soil, and there is a range of technologies used for this. Some slow-release fertilisers are not coated, but they dissolve slowly or are broken down slowly by microbial action. An example is urea-formaldehyde which is used in Grotabs®.

Controlled- and slow-release fertilisers have promise to reduce the risk of nitrate leaching from starter fertilisers in situations where N or P fertiliser is needed but the crop will take up very little of it in the first 4–6 weeks after planting. Some of the products have been available for many years, but cost issues have confined them mainly to amenity horticulture. Field testing of cheaper products such as Smartfert under New Zealand conditions is at a young stage. If indeed those products meet the manufacturers' claims to improve nutrient-use efficiency then some of the application rates currently recommended by the manufacturers appear excessive (Eko360 2014).

Liquid fertilisers in New Zealand are made by dissolving solid fertilisers (e.g. urea) in water. **Fertigation** is the application of liquid fertilisers through an irrigation system at intervals during crop growth. It is used mainly for soluble nitrogen fertilisers. It can be very effective at matching the timing of nutrient supply to crop demands and reducing the risks of leaching. A potential disadvantage is when wet weather makes irrigation inadvisable, so N applications may fall behind schedule.

Suspension fertilisers are sometimes injected into the soil. They are a fluid, made by mixing finely-ground fertiliser with 40–60% water by weight. A saturated solution is formed, with the rest of the ingredients suspended as fine particles. A gelling agent or a clay such as bentonite may be added to slow the settling of the fertiliser particles, but usually agitation is still required just before application.

Foliar fertilisers come in a variety of products derived from other fertilisers, seaweed extracts, fish waste, blood, etc. They are usually applied in dilute form because concentrated nutrient solutions sprayed onto foliage can stress the plants. The actual amounts of nutrients applied can be very low, and foliar applications are mainly used to complement solid fertilisers. However, liquid fertilisers may have a place for the short-term requirements of a crop and where weather conditions make solid fertiliser applications inefficient. Trace element sprays can be effective for overcoming some specific deficiencies, especially those linked to soil conditions such as dry topsoils and high pH.

Composts and organic waste materials like blood and bone are also sometimes used to supply plant nutrients. They have an advantage over mineral fertilisers in that they also supply organic matter that will benefit soil quality. A disadvantage is usually they are not very concentrated in terms of mineral nutrients, so large applications are needed. They supply N, P and S over time as the composts are decomposed by soil microbes. This can be an advantage or a disadvantage depending on the urgency for plant uptake. Nutrient concentrations may vary greatly between batches of composts so it is important to obtain a laboratory measure of their composition.

Microbial-based fertilisers or soil amendments are sometimes sold with claims to improve the efficiency of nutrient use. Growers are urged to check for independent, scientifically credible research into their effectiveness.

Plant establishment and starter fertilisers

Placing fertiliser too close to seeds or transplants can impair plant establishment (Cooke 1982; During 1984). This is caused by ammonia release from N fertilisers or the osmotic (salt) effect of the fertiliser. Maximum damage occurs where there is sufficient soil moisture to commence fertiliser dissolution and seed swelling but insufficient to disperse and dilute the fertiliser through the soil. Ideally seed and fertiliser should be 2–5 cm apart.

Fertiliser rankings according to risk of germination damage are shown below.

Least risk	Serpentine, dicalcic superphosphate
	Superphosphate
	Nitrophoska and Milla range
↓	Monoammonium phosphate
	DAP, Cropmaster 15, Crop Zeal 15
	Cropmaster 20, Crop Zeal 20, SOA
Most risk	Urea, MOP, boron fertilisers

General recommendations

- Do not sow more than 20 kg N/ha as urea with the seed. For other N fertilisers sow no more than 30–50 kg N/ha with the seed, and always try to maintain separation between fertiliser and seed.
- With small-seed crops (e.g. brassicas) use reverted superphosphates (superphosphate products that have been combined with lime and water).
- Banded side dressings of N fertiliser should be at least 10 cm from the plant.

Soil pH and liming

For optimal yield, the required soil pH varies between vegetable crops (refer to the specific chapter for each crop). Yield and quality can be reduced if pH is too low or too high – but for different reasons.

To raise soil pH, a silt loam on average requires 1 tonne of good quality lime (80% $CaCO_3$ equivalent), for each 0.1 unit increase (Roberts & Morton 2016). A higher rate will be required for clay soils or if the $CaCO_3$ content of the lime is less than 80%.

Using finer lime than AgLime and incorporating it will speed the process of raising soil pH, but the size of the increase in soil pH depends on the rate of lime applied (Craighead 2005).

Normally about 2.5 t/ha of lime is required every 3–5 years to maintain soil pH. The frequency increases with greater rainfall, irrigation and use of N fertiliser. Applications should be 3–6 months before the crop is sown – but see the recommendations for specific crops.

To lower soil pH is more difficult and can be expensive. Soil is acidified slowly by nitrifying soil bacteria. It can be acidified rapidly by addition of compounds such as ferrous sulfate or various alums, but this is expensive. Application of finely divided, elemental S will acidify soil more slowly as it is slowly oxidised to sulfuric acid by soil microbes. There are no general recommendations for rates and timing, though for blueberries (Haynes 1988) it is suggested that 1–1.5 t S/ha is required to lower soil pH by one unit.

Nitrogen fertilisers that contain urea or ammonium can acidify soil (Cooke 1982; MacLaren & Cameron 1990).

		kg of lime to neutralise 100 kg of fertiliser
Least effect	Calcium ammonium nitrate	30
	DAP	40
↓	Urea	50
Most effect	SOA	210

Economic matters

Applying more fertiliser than required reduces the profit to be made from the crop and increases the risk of N and P loss to water bodies. Too little fertiliser reduces both yield and profitability. The fertiliser rate that gives the best financial return is unique for each situation. It depends on the price the grower will receive per tonne of yield, the cost of the fertiliser and how responsive the crop is to the fertiliser. The responsiveness of the crop depends strongly on the soil test values.

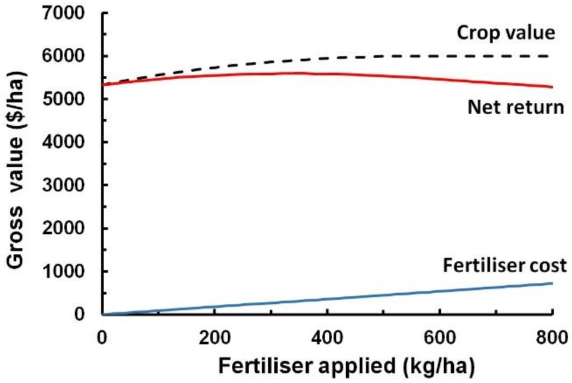


Figure 1-5. The economics of applying fertiliser. This example is for DAP fertiliser applied to sweet corn with a potential yield of 30 t/ha. The calculations assume crop value is $200/t, fertiliser costs $900/t, and without fertiliser soil N and P are limiting yield by 13%. Costs rise in simple proportion to the fertiliser rate, but the yield (and crop value) increases less and less. The best net return here occurs at a fertiliser rate of 320 kg/ha.

Usually, the financial gain is better if the fertiliser is applied to achieve slightly less than the potential yield. Even so, the rate of nutrients applied to crops should be determined by economic *and* environmental matters.

Environmental matters

Nitrate Leaching

Cultivation

- Minimise the time between harvest and establishment of the next crop.
- Avoid winter fallow, particularly after pasture, clover seed or grazed forages.
- Minimise depth and intensity of cultivation to reduce breakdown of organic matter.

Fertiliser N application

- Use fertiliser N rates that minimise residual mineral N – nitrate and ammonium left in the soil at harvest.
- Apply as little N fertiliser as possible in autumn and winter, and no more than the crop can take up at that time.
- Split applications to match plant N requirements with N supply.
- Avoid excess irrigation soon after the application of N fertiliser.
- If soil temperature is low, apply lower rates of N.

For more information see FAR (2012a).

Volatilisation of N fertilisers

Five to twenty percent of the N from N fertilisers may be lost as ammonia gas (Bishop & Manning 2011). These volatilisation losses are enhanced by windy conditions, high soil temperatures, lack of crop cover and high rates of N fertiliser.

Ammonia losses from urea are about twice that from di-ammonium phosphate and ten times greater than from ammonium sulfate. Urea is readily converted to ammonium by the urease enzyme in soil. This raises the soil pH around the granule which enhances volatilisation by converting ammonium ions to ammonia.

Volatilisation losses from urea applied to the soil surface can be minimised if there is 5 – 10 mm of rainfall or irrigation within 8 hours (Zaman et al. 2013). Unfortunately this is not a practical solution on most farms. This requirement for water straight after urea application is especially important if the soil is moist since this small amount of moisture is sufficient to start the breakdown of urea to ammonium but insufficient to disperse it sufficiently by absorption into the soil.

In some urea fertilisers (e.g. SustaiN and N-Protect®) the granules are coated with urease inhibitors that slow down the rate of volatilisation. They can reduce the amount of N lost by 50%. The return on urease inhibitors for the extra cost is maximised in situations where high rates of N must be spread on the soil surface; they can reduce the risk of ammonia loss and increase flexibility in the timing of application.

For vegetable production ammonia volatilisation is best reduced by incorporating N fertilisers into the soil. For side dressings this is best done by knifing them into the soil especially if there is deep placement and the soil groove is covered.

For more information see FANZ (2013) and FAR (2012b).

Cadmium

Cadmium (Cd) is a naturally occurring heavy metal that has gradually accumulated in our soils through the application of P fertilisers and can be detected in varying amounts in root and leafy vegetables (Abraham et al. 2016; Cavanagh et al. 2016; Cavanagh et al. 2018). It is worth noting that some of the published research that claims to have measured Cd uptake by vegetables (e.g. Cavanagh et al. (2018)) has measured only Cd concentration in the marketable plant organs not plant uptake. Doubtless, plant uptake of Cd can be influenced by many factors. In general, we can expect that uptake is reduced by using low accumulating plant species and/or varieties, improving soil organic matter, increasing soil pH to the high end of the optimum range, alleviating any zinc deficiency and maintaining recommended amounts, avoiding chloride in irrigation water, and minimising localised acidification effects. Growers should consider if there is a risk of excessive uptake with the crop varieties and land they use, and if so how to deal with it. Monitoring using plant tissue analysis of harvestable plant parts is advised.

The Tiered Fertiliser Management System (TFMS) has been designed to manage the accumulation of soil Cd from P fertilisers. In addition, the TFMS recommends field management practices to minimise the uptake of Cd in horticultural crops.

Tier 0 indicates no limitation on choice or rate of P fertiliser. However, routine soil Cd assessment should occur every 5 years.

Tiers 1 and above apply if soil Cd concentrations are greater or equal to a trigger value of 0.6 mg Cd/kg soil.

The consequences range from Tier 1 where there is a slight restriction on rate and choice of P fertiliser products, through to the top tier where no further accumulation of Cd is acceptable (so there are strong restrictions on P fertiliser use). At or above the top tier there should be a detailed site-specific investigation to identify and risks and pathways for potential harm.

Key point: Are Cd tests needed?

Excessive plant uptake can occur at any soil cadmium level, depending on species/variety and soil factors. *Monitoring of harvested produce is advised.*

To understand and manage the risks associated with soil Cd, all farmers applying P fertiliser should undertake soil tests for Cd, and implement the tiered Fertiliser Management System

If the soil Cd concentration is <0.6 mg Cd/kg soil, Tier 0 applies and no restriction on P fertiliser use is required – but repeat the sampling in 5 years.

Management of plant uptake may be required at any Tier level, including Tier 0.

For the background and details of the TFMS and sample collection procedures see the resources tab of the web site www.fertiliser.org.nz.

1.4. Code of Practice for Nutrient Management

To assist growers with safe, responsible and efficient use of fertilisers, the Fertiliser Association of New Zealand and Horticulture New Zealand (FANZ) have each developed a *Code of Practice for Nutrient Management* (Anon 2014; FANZ 2013). These provide practical advice on effective nutrient management and Best Management Practices for the most efficient use of nutrients. The codes are complimentary; the Horticulture New Zealand code includes some specific checklists for vegetable growers, whereas the FANZ code is more detailed, especially around nutrients other than nitrogen, fertiliser contaminants, nutrient management plans, and the handling and application of fertiliser.

Using these codes helps growers achieve their production goals and meet their responsibilities under the Resource Management Act. Neither code contains prescriptive practices (or “rules” about use), and neither attempts to recommend nutrient requirements for specific crops. Both provide flexibility and allow for site-specific solutions.

The FANZ code is especially useful where it focusses on significant environmental considerations, including:

- Determining the land’s requirements for nutrients
- Nitrate leaching to groundwater
- Surface water contamination from fertiliser runoff

- Contamination of surface water from direct application
- Potential effects on third parties.

Some examples of the FANZ code's recommendations for these are given below.

Determining the land's needs for nutrients

- Apply fertiliser to achieve an identified response or objective (not as a "routine" procedure).
- Prepare a *Nutrient Budget* and operate a *Nutrient Management Plan* in consultation with your farm or fertiliser nutrient management adviser.
- Test soil and plant tissue.
- Have a working understanding of the principles underlying fertiliser use.
- Use the *Code of Practice for Nutrient Management* and the Fact Sheets included.

Minimise nitrate leaching to groundwater

- Match nitrogen application to plant requirements and rate of uptake.
- Split fertiliser applications, applying smaller amounts more often.
- Avoid application if heavy rain is forecast or if the ground is saturated.

Minimise surface water contamination through run off

- Split fertiliser applications, applying smaller amounts more often.
- Avoid application if heavy rain is forecast or if the ground is saturated.
- Set realistic growth rate targets, and match application to requirements.
- Use a *Spreadmark*-certified spreader where appropriate.

Avoid contamination of surface water from direct application

- When windy (anything greater than 5 kph), apply when it is blowing away from open water.
- Be fastidious about accurate and uniform application, and containing fertiliser to application zone.
- Use fertiliser with larger particle sizes (particles of less than 1 mm have poor ballistic properties).
- Establish a riparian strip or allow for a realistic buffer zone.

Minimise third party effects

- Consider noise implications, and choose appropriate time.
- Consider sensitive times and places (for example schools, or neighbour practicing organic farming) and choose appropriate time and application techniques.
- Winds above 5 kmph can cause drift, so consider particle size and application method.
- Be fastidious about accurate application.
- Be neighbourly and tell others in advance, and of changes to plans.

For more detailed information on the Code and for the series of Fact Sheets relating to it (including *Spreadmark*) visit www.fertiliser.org.nz

1.5. Nutrient Management Plans & Nutrient Budgeting

A nutrient management plan (NMP) is a written plan that describes how the major plant nutrients will be managed annually on a particular area or property. Implementing the plan should optimise productivity, reduce nutrient losses and avoid, remedy or mitigate adverse effects on the environment. *It is recommended that advice is sought from an NMACP-accredited management adviser to develop nutrient management plans and nutrient budgets*. A good NMP should:

- Ensure that nutrient management meets all legal and industry requirements
- Include a nutrient budget that compares all inputs and outputs
- Achieve desired changes in nutrient contents and production (e.g. increasing soil fertility from a poor base to maintain or improve production capacity)
- Minimise the cost of supplying nutrients and avoid wasted spending on unnecessary or unused nutrients
- Promote efficient and effective nutrient use
- Minimise the risk of adverse environmental effects
- Consider the land manager's personal objectives.

A sample NMP template is available in the Code of Practice for Nutrient Management.

Nutrient budgets and Overseer®

Nutrient budgets summarise the nutrient inputs and outputs from land. They are important tools for sustainable management and can be devised at scales from the paddock up to whole landscapes. Increasingly, regional councils and accreditation schemes are using them.

It is prohibitively expensive to measure directly the flows of nutrients in a farm system. The only viable option is to use nutrient budget models that use unique input data for each property. Normally these budgets calculate offtakes and losses of nutrients on the basis of typical or expected yields, and inputs that the user chooses.

Key point: What's the use?

Nutrient budgets can provide a check on the sustainability and potential environmental impacts of nutrient management practices. They do not calculate yield or nutrient requirements of crops, nor do they indicate if using fertilisers will be profitable.

If nutrient inputs (e.g. from fertilisers) are known, and offtakes in harvested produce are estimated from yields and typical crop composition data, then simple nutrient budgets for vegetable crops can be constructed on paper or in a spreadsheet. However, these can seriously underestimate the potential for adverse environmental impacts unless proper account is made for processes like leaching, mineralisation and N-fixation by legumes. For some crops, nutrient budgets can be constructed using information gained from crop or nutrient management software although this can be challenging to extract and document.

Overseer is a decision support system for calculating nutrient budgets using long-term weather data. It models the cycling and flow of nutrients to estimate the:

- Losses of key nutrients including N and P (which can have environmental impacts)
- Losses of agricultural greenhouse gases
- Balance of inputs and outputs of essential plant nutrients to indicate sustainability of nutrient supply to plants
- Effect of different crop rotations, nutrient inputs, residue management and fallow periods on availability or losses of nutrients.

The best method of interpreting Overseer's output is to use trends of the nutrient balances and losses over several years; it cannot be used to represent within-season variation. The long-term equilibrium approach underlying Overseer can work well for pastoral agriculture and many cropping situations. Current (2018) versions lack sufficient flexibility, capability and crop-specific data for some vegetable-growing businesses (Hume et al. 2015; Khaembah & Brown 2016; Willis 2018). This is especially the case where the total length of a crop rotation lasts several years and involves several different crops, and where crops grown in the same year have disparate needs and impacts. One possible solution is for the user to set up surrogate or proxy rotations that fit the software's restrictions but probably have similar net behaviour to the actual rotations. Identifying and adequately testing those may require specialist assistance.

Some regulatory authorities have adopted Overseer to provide information on the sustainability of agricultural production, and for assessing and controlling the potential for nutrient losses to the wider environment. Overseer can offer useful insights into those matters, but as noted above the software has important limitations for some vegetable-growing businesses. Where use of Overseer is required of growers, often the best approach is via an accredited consultant, such as a Certified Nutrient Management Adviser, who has a good understanding of the programme and is trained to fully interpret its output.

Overseer Ltd provides some guidance and suggestions on the use of Overseer in regulation (Freeman et al. 2016; Watkins & Selby 2015; Willis 2018).

For more information visit www.overseer.co.nz or www.fertiliser.org.nz/Site/faq.

2 Making nutrient recommendations

The optimum plan for supplying nutrients to vegetable crops can vary a great deal between situations. Even for a single type of crop there is no single best way for all growers. The main factors that influence the likely outcomes from nutrient amendments from fertilisers and composts are as follows:

- Potential yield – this dictates the maximum amount of nutrients the crop needs, and is influenced mainly by weather, the plant population and quality considerations for marketing (e.g. plant size). It is defined in Chapter 1 Potential, field and marketable yields.
- Non-nutritional factors that lower potential yield to field yield (Chapter 1 Potential, field and marketable yields). Examples are water stress, poor soil structure, pests and diseases.
- Chemical fertility of the soil (quantified by soil testing).
- Nature of the amendments and how they are applied – are the nutrients quickly or slowly available, are they broadcast or banded, when are they applied relative to crop needs? (*Right amounts, Right location, Right time.*)
- Value of the crop compared with the costs of the amendment (see Economic matters in Chapter 1).
- Risks of nutrients being lost to the wider environment (see Environmental matters in Chapter 1).

There are two major components of a fertiliser nutrient recommendation:

1. How much nutrient is required to grow the crop?
2. How much nutrient is needed for maintenance, i.e. will be needed to replace that removed in the crop (offtake)?

It is important to remember that the nutrient supplied to a crop is the *total* of that from the soil *and* that from amendments like fertilisers.

Key point: too much nutrient?

If the nutrient supply is small, additions are often needed to achieve potential yields and quality.

At a certain rate of supply though there will be very little to gain from supplying extra, and the best policy is to apply only enough to maintain the soil fertility.

At a still higher rate of supply, yield and quality may start to decline, or the risk of significant environmental damage becomes unacceptable. Under those circumstances, it is best to not apply more nutrient – even if this means the crop will deplete the soil slightly.

Many factors influence the level of supply at which the grower should switch to maintenance applications only, or stop applying any further nutrient. The most important factors include the potential yield of the crop and interactions between nutrients.

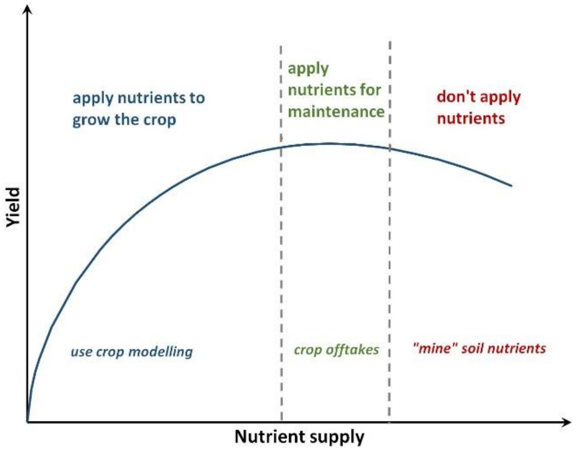


Figure 2-1. Typical response of crop yield (or quality) to the total supply of a single nutrient from the soil and from amendments like fertilisers or composts. The upper limit of yield is set by crop characteristics and the weather – you cannot increase this by adding more and more nutrients. For some nutrients and crops the decline in yield at high levels of nutrient supply can be very pronounced, but for others it can be very gradual.

2.1. Nutrients to grow the crop

First we need to know if nutrient additions like fertilisers are necessary to achieve the target crop yield and quality. This depends on the amounts of nutrients already in the soil, so:

Amount of extra nutrient required = amount of nutrient required for target yield – the soil supply of the nutrient

Often the uptake of nutrients for each crop is *not* a reliable estimate of the amount of nutrient that should be applied to grow vegetables. Some vegetable crops have a strong capacity to take up nutrients in greater quantities than required for maximum yield ("luxury uptake"). Others (like buttercup squash and onions) may have sparse root systems and a short time to take up the nutrients they need. To achieve a high rate of uptake by each mm of root these crops need high concentrations of nutrients in the soil. Then the optimum fertiliser applications may be greater than plant uptake. However, the disparity between uptake and the fertiliser rate for the best yield can be reduced by careful placement and timing of fertiliser applications.

In this book, computer models based on field research have mostly been used to estimate the amount of nutrient that needs to be added in order to "grow the crop". The results are summarised in tables that relate the nutrient application rate required to crop potential yield and the initial soil test nutrient concentration.

Recommendations from models

For a number of vegetable crops, New Zealand research has considered all or most of the factors that will influence the response to supply of the major nutrients. Developing general recommendations for those crops is still complex, but computer models can help greatly. That is the main approach used in this book. The models most used are adaptations of PARJIB (Reid 2002) and the Potato Calculator (Jamieson et al. 2006). These have been calibrated for each crop type individually using results from field experiments in New Zealand.

PARJIB relates the yield of each crop to the amounts of N, P, K and Mg supplied from both the soil (based on New Zealand standard soil tests) and from amendments like fertilisers. It takes into account potential yield and interactions between the effects of these nutrients and those of soil pH. The model also accounts for differences between the efficiency of nutrients already in the soil compared with those in broadcast or banded fertilisers.

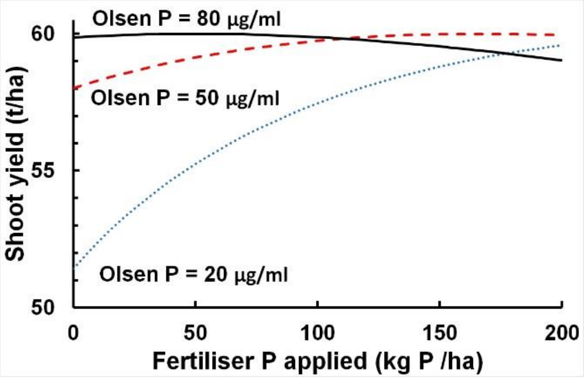


Figure 2-2. Lettuce response to fertiliser P at three different concentrations of soil Olsen P, simulated using the PARJIB model (Reid 2002) specifically adapted for this book. The potential yield was 60 t/ha of shoot biomass (30 t heads/ha), and there were no limitations from other nutrients, pH or soil water. The rate of applied P required to grow the crop decreases as Olsen P increases.

The models accurately mimic the way that crop yields respond to nutrient supply, with "diminishing-returns" style curves, with an optimum nutrient supply level that depends on the crop's potential yield. For some crops yield decreases if nutrient is supplied beyond that optimum (Figure 2-2). For the recommendations here the models examined yield response to nutrient supply under different scenarios. These included different potential yields and situations where yield was also limited by factors such as water stress.

For each scenario, the models simulated the response curves individually for N, P, K and Mg when the other nutrients were optimally supplied. Recommended fertiliser rates were chosen for the crop to achieve 99% of the maximum yield. This avoided the very high fertiliser rates often necessary to achieve potential yields when the response curve is very gradual. It was not practical to identify economically optimum fertiliser rates; there are too many variations in fertiliser and crop prices to include in a book of this size.

Key point: Nutrient uptake and yield response are not the same thing

When soil test values are low, crops may yield best at fertiliser rates that exceed their actual uptake of the same nutrients. This is probably because the crops have sparse root systems and a short growing season. However, the disparity between uptake and the fertiliser rate for the best yield should be reduced by careful placement and timing of fertiliser applications.

PARJIB and soil bulk density

The PARJIB model calculates the nutrient supply from the soil on the basis of soil test results expressed in kg of nutrient per hectare. To do this it converts standard soil test results using a formula that includes two different bulk density values (both in g/ml):

1. ρ_{lab}, the bulk density or volume weight measured after air drying and sieving in the laboratory prior to chemical testing
2. ρ_{field}, the dry bulk density of the top 15 cm of soil in the field *at the time of planting*. This is rarely measured, and because it often reflects recent cultivation the values are usually rather less than the values reported in soil surveys.

For the generic recommendations in this book, representative values of ρ_{field} and ρ_{lab} had to be assumed. The assumed values vary from crop to crop, and are usually based on the mean values measured in the datasets used to fit the PARJIB model for that crop. If site-specific values of ρ_{field} and ρ_{lab} are known then this books generic recommendations can be adjusted as follows:

Site specific recommendation	=	generic recommendation	x (ρ_{field}/ρ_{lab}) x	(ρ_{lab}/ρ_{field})
(kg element/ha)		(kg element/ha)	actual values	assumed values

The crop chapters in this book indicate the bulk density values used to derive the generic recommendations.

Using critical nutrient concentrations in the plant

This approach is increasingly being used overseas (e.g. in the UK and Germany).

Crop yield declines if the concentration of any nutrient in it is less than a critical value. So, if you know that, then you can calculate the amount of nutrient that it must take up to reach any particular potential or target field yield; you simply multiply the critical concentration by yield (making sure the units are compatible). This provides a clear indication of the amount of the nutrient that must be supplied from the soil and fertilisers together, assuming all the fertiliser is used efficiently.

A complication is that the critical concentrations of nutrients like N, P and K must be measured for the whole plant (not just leaves) and these values generally change as the plants get bigger (see Plant nutrient concentrations and nutrient uptake in Chapter 1). This means that for each nutrient you need to know the critical concentration when the plants are at the same dry mass at which you want to harvest them. For some crops these values are known, and nutrient requirements can be forecast using them. This is the main approach used to forecast N requirements of vegetable and arable crops in the UK (Defra 2010).

In this book, the fertiliser recommendations for beetroot, cabbage, broccoli, cauliflower, silverbeet and spinach have been calculated using published relationships between plant dry mass and critical N concentrations.

Using target soil test values

There has not been enough research to build and calibrate models for all crops in New Zealand. For some crops, however, there are indications from the scientific literature of soil test ranges that do not appear to limit crop yield, and nutrient recommendations can be made on that basis.

The target soil test value at planting time is usually defined as the value needed for the crop to achieve 95% of its maximum marketable yield. The approach assumes that yield varies in a simple way with the soil test values. Target values for P and K were used extensively in earlier fertiliser recommendations for New Zealand.

Soil test targets can work well, but are often less reliable than use of a properly checked and calibrated model. One concern is that supporting evidence for the target ranges is surprisingly difficult to find. Be wary especially of targets based on overseas evidence – always check that they refer specifically to the same soil test method that is used in NZ. Olsen P tests are standard throughout much of the world, but not everywhere. The New Zealand methods for measuring and reporting pH, cations and N differ from those in most other countries.

For field vegetables, the approach seems to have been tested most thoroughly for Olsen P. For some crops identifying a target Olsen P appears straightforward (e.g. Figure 2-3a). For others there may be no convincing relationship between Olsen P and yield (e.g. Figure 2-3b) and it is hard to justify the target ranges used in earlier recommendations.

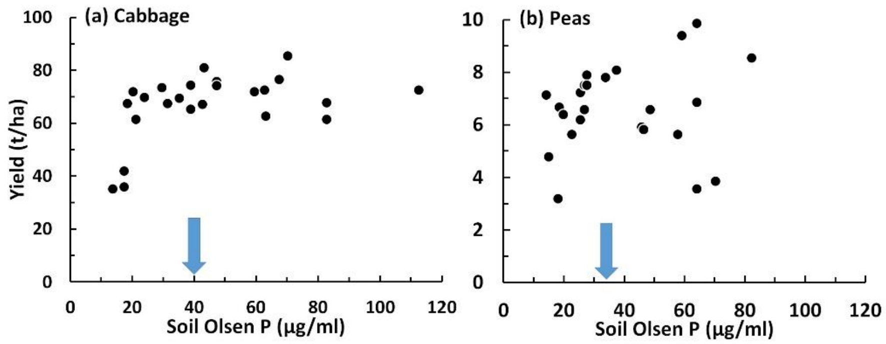


Figure 2-3. Relationship between yield and soil Olsen P for cabbage and peas grown at Levin (Prasad et al. 1988). The arrows indicate the target Olsen P identified by Prasad et al.

For nutrients like K and Mg it is hard to find supporting evidence that comes close to the quality of that for the Olsen P targets. Very few field experiments with vegetables in New Zealand demonstrate response curves to either soil test values or fertiliser applications for these nutrients. Experiments at Pukekohe over 4 years failed to find a consistent relationship between QT K and potato yield. Previously recommended target ranges were perhaps estimated as the lowest soil test value at which no fertiliser response was measured. There is almost no experimental information available on target soil test values for N. So, for vegetable crops, nutrient recommendations based on target soil test values should be regarded with considerable caution.

In this book, the P and K recommendations for beetroot, cabbage, broccoli, cauliflower, silverbeet and spinach were calculated using target ranges.

Using target values to make a nutrient recommendation

Targets are often quoted as ranges.

If a soil test value is more than the target range then either:

- Withhold fertiliser and allow the value to drop into the target range; or
- Apply a maintenance nutrient rate.

There is an environmental cost to the second option in that there is a greater risk of P contamination of water bodies. Calculation of maintenance nutrient rates is explained later in this chapter. Usually they are applied before planting.

If a soil test value is within the target range then apply a maintenance nutrient rate.

If a soil test value is below the target range then nutrients should be applied before planting to increase the soil test level into the target range. Use the following guidelines to calculate the amounts of nutrient to apply. They are all calculated to raise the soil test value in the top 15 cm of soil only.

To raise soil Olsen P

To raise Olsen P by one unit (µg/mL) requires

25 kg P/ha (range 20–30 kg P/ha) on volcanic ash (Allophanic and Granular) soils

13 kg P/ha (range 10– 6 kg P/ha) on peat (organic) and sands (recent) soils

10 kg P/ha (range 3–16 kg P/ha) on sedimentary (recent and brown) soils.

To raise soil QT K

On average to raise QTK by one unit requires 50 kg K/ha (range 30–70) for the volcanic ash and 33 kg K/ha for the Brown sedimentary soils. With Recent soils the exact clay types present may be very important and it is best to check local experience with each specific soil. For example for the Hastings series, the amount of K fertiliser needed for a silt loam might be more than for a clay loam (Wood et al. 1986).

On some peat soils, for example those in Hawke's Bay, it is very difficult to increase QT K values even with high capital rates of application of K fertiliser.

2.2. Maintenance nutrient applications

The offtake, or amount of nutrient removed in the harvestable portion of the crop, represents the loss of nutrients from the soil. This rate of nutrient is usually referred to as the maintenance application.

Key point: Is it necessary?

Maintenance applications should be made only if no nutrients have been applied to grow the crop. Unless soil test values are high, nutrient applications to grow the crop are usually greater than maintenance rates.

Usually in vegetable cropping, maintenance nutrient applications are best made before or during the crop's growth. Strictly, maintenance rates are most accurately calculated (and applications made) after you know the yield and nutrient offtake of the crop – but often this is impractical, particularly because soil tests should be taken for the next crop:

- An extra round of fertiliser applications may complicate interpretation of those soil tests because of slow equilibration within the soil.
- The soil test results will reflect any depletion by the previous crop. Nutrient applications to grow that next crop will be calculated from those soil tests and will correct that depletion if it is likely to affect crop performance.
- The grower may want a decrease in soil test values for best performance of the next crop.

The first step to calculating maintenance applications is to estimate the amount of plant material that will be removed from the field. If you are forecasting a target yield, wherever possible use information for the same crop grown in the same general location.

The next step is to identify the most likely nutrient offtake per tonne of yield. There is no standard data source for this in New Zealand, but there are options.

Sometimes information on typical nutrient concentrations in the crop can be supplied by accredited chemical testing laboratories within New Zealand. If not, overseas data may have to be used. Useful sources of uptake and offtake (removal) data include USDA (2018) and IPNI (2018).

Key point: Check the units

If you are using data from overseas, be sure you use values quoted in kg of each element per tonne of yield. Overseas they often quote values in kg P_2O_5/t (multiply by 0.43 to get kg P/t) and kg K_2O/t (multiply by 0.83 to get kg K/t).

Also check if the values are quoted for dry or fresh yields

For each nutrient multiply the target yield (t/ha) by the estimated nutrient concentration (kg nutrient/t) to get the recommended maintenance nutrient application rate.

Is maintenance always best?

Generally, the risks of nutrient losses to groundwater and run-off will be greatest from soils with high soil-test values. So if soil test values are already above the concentrations that would limit crop growth it could be environmentally damaging and financially pointless to apply maintenance fertiliser. For some crops the figures available for K removals (here and in OVERSEER®) reflect luxury uptake – forever replacing these removals would encourage further unnecessary uptake.

Maintenance applications of N by soluble fertilisers are not recommended. Except in organic production systems, N fertiliser is applied for crop needs, not to replace losses, because most soils do not retain N and it will be subject to leaching. To minimise leaching in the fallow period following harvest growers should aim for soil mineral N to be as low as possible when the crop is harvested. This restriction need not apply to applications of composts, which slowly release mineral N.

2.3. Nutrient recommendations for crops not in this book

Approaches that can be taken include:

- *Using target soil test values*. Target ranges may be quoted in earlier publications, but be cautious over their reliability.
- *Using estimated uptakes*. For some crops uptake can be calculated from critical nutrient concentrations (see above). Values for N in particular may be available from the scientific literature, but there is much less data for P and K, and the calculations can be tricky.

- *Using estimated offtakes*. For some crops, the only suitable information available may be the target yield and overseas data for nutrient content of harvested plant material (see above section on maintenance fertiliser applications). This approach may underestimate nutrient requirements when soil test values are low, and overestimate it when they are high.

2.4. From recommendation to application rates

The nutrient recommendations in this book are given as kg of the nutrient per hectare. For each nutrient there will be a number of ways of applying the recommended amount using the fertiliser products available locally. Products differ in their composition so it is important to follow a reliable way of calculating how much of each product is needed.

The N-P-K-S rating of a fertiliser indicates the percentage amount of plant nutrients in it. For example a 15-10-10 fertiliser contains 15% N, 10% P, and 10% K. To calculate the quantity of fertiliser needed to apply a given rate of nutrient, use the following formula:

$$\text{Rate of fertiliser application (kg/ha)} = \frac{\text{rate desired for nutrient (kg/ha)} \times 100}{\text{nutrient in fertiliser (\%)}}$$

Example: A nutrient recommendation is for 30 kg N/ha, 20 kg P/ha, and 30 kg K/ha. What rate of a 15-10-10 fertiliser should be applied?

N : rate of fertiliser = $\frac{30 \times 100}{15}$ = 200 kg/ha

P : rate of fertiliser = $\frac{20 \times 100}{10}$ = 200 kg/ha

K : rate of fertiliser = $\frac{30 \times 100}{10}$ = 300 kg/ha

So, you cannot apply the required N, P *and* K with this fertiliser. Applying 200 kg/ha of 15:10:10 meets the N and P recommendations but will deliver only 20 kg K/ha. The remaining 10 kg K/ha that is required could be met by adding say some muriate of potash (0-0-50). The amount required will be (10 x 100 /50) = 20 kg/ha.

2.5. A final note

Irrespective of how a nutrient recommendation is arrived at, it must be consistent with the Code of Practice for Nutrient Management (FANZ 2013). In particular:

- Fertiliser application methods, placement, and timing must be arranged to minimise the risks of leaching, run-off or volatilisation. Generally this entails incorporating fertiliser whenever possible, and splitting N fertiliser applications.
- Recommended applications of P, K, and Mg should not be less than required for maintenance of soil nutrient reserves, except if soil test values are already excessive (see Is maintenance always best?).

3 Beans for processing

Beans grown for processing in New Zealand are usually *Phaseolus vulgaris* L. and are often referred to as process beans, dwarf beans, or French green beans. They are grown mainly in Canterbury and Hawke's Bay. Like peas, beans are legumes capable of fixing atmospheric nitrogen (N) for their own use, and are sometimes regarded as a useful crop in a rotation because of this. However, compared with peas, process beans are grown at about half the plant population density (usually <45 plants/m^2) and have a shallower root system (by reputation usually less than 50 cm deep). So usually they have sparser root systems that have to support similar amounts of shoot growth. A consequence is that unlike peas, beans have shown strong responses to soil nutrient levels and fertiliser applications (Tregurtha et al. 1998; Wilson et al. 2000; Wilson et al. 1998).

3.1. Potential yields

A comprehensive model of potential yield in beans has not been published, but initial work has emphasised the importance of air temperatures and interception of light by the canopy (Wilson et al. 2000). The partitioning of plant dry matter to harvestable pods is an area that still requires research, and there may be substantial, and so far unexplained, differences between crops grown in the North and South Islands in the number of pods supported per plant. In Canterbury, marketable bean yields are usually <20 t/ha, but a few crops manage 30 t/ha, which is probably close to the potential there and in Hawke's Bay (Reid et al. 2016b; Wilson et al. 2000).

These recommendations assume a potential yield of 30 t/ha of fresh beans in pod, equivalent to about 3.3 t/ha of dry matter, and that 90% of the pods are removed from the field.

3.2. Nutrients to grow the crop

Here fertiliser recommendations for N, P and K were calculated using a combination of modelling and likely nutrient offtakes.

The modelling was a reanalysis of work carried out in New Zealand for VegFed (Tregurtha et al. 1998; Wilson et al. 1998). The variety examined was Labrador, grown at five sites in Canterbury. The experiments covered a wide range of soil fertility. Pooled results from these sites were used for fitting the PARJIB model for yield response to nutrient supply (Reid 2002; Reid et al. 2002c). The model accounts for variations in nutrient supply from both the soil and fertilisers. The fitted model described the field data well, but the range of fitting data was limited to N, P and K rates less than 46, 32 and 32 kg/ha respectively. These limits arose because in the experiments fertilisers were either broadcast or banded "down the spout" with the seed (and higher rates risked seedling damage using the latter method). Broadcast fertiliser was largely ineffective, but strong responses to the banded fertiliser were observed.

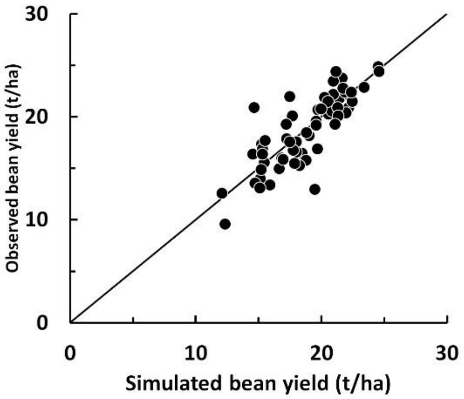


Figure 3-1. Performance of the PARJIB model for process beans. Measured yields are plotted against the simulated values from the model after calibration. The plotted line is the line of perfect agreement.

The relatively small range of fertiliser rates available for model fitting meant that plateau regions for N, P and K responses could not be identified reliably. For N and P, recommendations based on the model are restricted to rates that can applied with the seed. For K, larger applications may be desirable for fertility maintenance, and in those cases applications banded away from the seed may be used also.

Soil tests

Before the crop is planted carry out soil testing from 0–15 cm depth *in each paddock.* Choose the standard soil testing suite (pH, Olsen P, QT Ca, K, Mg and Na, CEC and soil volume weight) PLUS 'Available N' (anaerobically mineralisable N) in kg N/ha.

Key point: Assumed soil bulk densities

The generic recommendations for beans assume the bulk density in the field (ρ_{field}) is 1 g/ml and the bulk density of air-dried sieved soil in the laboratory (*volume weight*, ρ_{lab}) is 1 g/ml. These values can be used to make the nutrient recommendations below more specific to a site if measured values of ρ_{field} and ρ_{field} are known (see Chapter 2, PARJIB and soil bulk density).

Nitrogen (N)

Although beans can fix much of their own N, a low fertiliser N rate at sowing often increase yields.

- If soil Available N < 150 kg N/ha then apply up to 46 kg N/ha.
- If Available N > 150 kg N/ha then do not apply N.

If using soluble fertilisers, keep high salt-effect fertilisers from being too close to the seed (see *Plant establishment and starter fertilisers* in Chapter 1). If using fertilisers with a low to moderate risk of seedling damage (e.g. YaraMila and Nitrophoska ranges, Crop Zeal 15/Cropmaster 15) then apply up to 46 kg N/ha down the spout. If using fertilisers with a high risk of seedling damage (e.g. Crop Zeal 20/Cropmaster 20, urea); ensure there is separation between fertiliser and the seed and take especial care of this under dry conditions. Experiments have found broadcast fertiliser to be poorly effective for beans grown in Canterbury.

If using compost sources of N, incorporate these at least a month before planting so that there is time for the N to start becoming available to the plant.

Phosphorus (P)

Olsen P (µg/mL)	Recommended P application (kg P/ha) to grow the crop
<45	67
45–60	30
>60	nil

If using soluble fertilisers, keep high salt-effect fertilisers separate from the seed (see *Plant establishment and starter fertilisers* in Chapter 1). If using fertilisers with a low to moderate risk of seedling damage (e.g. superphosphate, Nitrophoska, YaraMila, Cropmaster 15/Crop Zeal 15) apply up to 30 kg P/ha down the spout (the rate might be limited by the capacity of the drill itself, but aim for fertiliser placement that separates seed from the fertiliser). If using fertilisers with a high risk of seedling damage (e.g. Cropmaster 20/Crop Zeal 20) ensure there is separation between fertiliser and the seed and take especial care of this under dry conditions. Do not side-dress P fertilisers as the plants will take up very little of the P applied.

If using compost sources of P, incorporate these at least 2 weeks before planting.

Potassium (K)

Soil QT K	Recommended K application (kg K/ha) to grow the crop
3	260
4	210
5	150
6	80
>6	nil

If using soluble K fertilisers, then apply up to 30 kg K/ha of the recommendation down the spout, but do not apply high salt-effect fertilisers like MOP this way (see *Plant establishment and starter fertilisers* in Chapter 1). If using fertilisers with moderate risk of seedling damage (e.g. YaraMila, Nitrophoska, Cropmaster 15) apply up to 30 kg K/ha of the total recommendation down the spout and apply the remainder of the recommendation 5 cm from the drill line. Fertilisers with a high risk of seedling damage (e.g. MOP) should be broadcast.

If using compost sources of K, incorporate these at least 2 weeks before planting.

Calcium (Ca) and lime

Yield or quality responses to fertiliser Ca are very unlikely in New Zealand because most soils contain large quantities of this nutrient, and much is applied in the form of lime to correct low soil pH.

There appears to be no definitive study of lime effects on process beans in New Zealand. Marked effects of low soil pH were noted in the modelling carried out for these recommendations, yield losses of 30–40% were indicated when soil pH fell below 5. Soil pH values in excess of 6.5 enhance the risk of trace element deficiencies.

- Apply lime only if pH is less than 5.5, targeting a pH of 6.0.
- Apply fine lime at least a month before planting.

Magnesium (Mg), sodium (Na), sulfur (S) and trace elements

There is no evidence that fertilisers for these nutrients are needed for process bean crops in New Zealand. However, the crop is reputedly vulnerable to Zn deficiency when grown on high pH soils. If Zn deficiency is suspected, the best treatment is probably foliar sprays applied at manufacturer's recommended rates. Foliar sprays are best applied in the early morning or evening to extend the drying time and the opportunity for the nutrient to enter the leaves.

3.3. Maintenance nutrient applications

Maintenance applications of any particular nutrient should be made only if none will be applied to grow the crop.

There appears to be no information available on nutrient uptake and offtake by process bean crops grown in New Zealand. Offtake values have to be calculated using overseas data.

Table 3-1. Estimated offtakes of N, P and K by a process bean crop where the yield removed from the field is 27 t/ha of pods. The values are based on data from USA (USDA 2018).

	N (kg N/ha)	P (kg P/ha)	K (kg K/ha)
kg nutrient/t pods	3.7	0.60	2.8
offtake by a 27 t/ha crop	100	16	76

Estimate maintenance application rates from the kg of each element taken up or removed per tonne of harvested roots (see Table above). For a crop where 27 t/ha pods are removed from the field the maintenance P application should be 27 x 0.6 = 16 kg P/ha.

For N, maintenance applications should be considered only under organic production systems using composts.

If Olsen P>75 then do not apply any maintenance P (allow Olsen P to decrease).

If QT K>10 then do not apply any maintenance K.

For methods of application of nutrients follow the guidelines for nutrients to grow the crop.

3.4. Plant nutrient analysis

Typical concentrations in the foliage or even whole plants are of little use. It is very difficult to establish critical concentrations of nutrient elements in beans grown in the field, and for N, P and K at least these critical concentrations decrease markedly as the plants get larger.

Table 3-2. Critical concentrations for whole plants (above ground) of beans grown in the UK (Greenwood et al. 1980a). Values are given on a dry mass basis.

Plant dry mass (g)	N	P	K
3	5.1	0.48	3.8
10	2.8	0.3	2.7
11	1.7	0.2	2.1

Most likely deficiency symptoms

Visual symptoms of nutrient deficiency are very unlikely in New Zealand bean crops. Damage from extreme weather, insects, diseases or sprays are much more likely to cause unusual appearance of the shoots. Helpful images are available from the Yara CheckIT app for mobile telephones (Yara 2017). On high pH soils Zn deficiency may appear early in crop growth; symptoms include pale green colours between the leaf veins and abortion of pods formed from terminal flowers.

4 Buttercup squash

Buttercup squash (*Cucurbits maxima* Duch.) for export and the local market is grown mainly in the North Island and Canterbury under a wide range of soil and weather conditions. An important feature of good buttercup squash crops is a very large growth rate per plant. The crop is grown at population densities of 15,000–22,000 plants/ha, producing about 11 t/ha of dry matter. So if all goes well, an individual plant may achieve a dry mass of about 500–730 g about 110 days from sowing. That is two to three times the growth achieved by individual plants in sweet corn crops grown for much the same length of time. The root system of buttercup squash has been studied little in the field. There are indications the root system may be very deep close to the planting line (Kristensen & Thorup-Kristensen 2007), although it appears sparse with exploration of the topsoil decreasing sharply with distance from the plants. So to maintain the nutrient uptake necessary for fast shoot growth squash requires the soil to be of quite high fertility, at least in the regions close to the base of the vines.

4.1. Potential and marketable yields

Potential fruit yields in squash are dictated mainly by the weather. In particular, the crop needs warm soil temperatures (at least 12°C and preferably >15°C) to germinate and emerge. After emergence, yield is strongly influenced by the amount of sunshine the crop can intercept, and rapid leaf growth is crucial (ready access to nutrients and water are important for this). Hot weather through the season can speed leaf growth but it will encourage faster maturation of the crop so that potential yield is not necessarily greater than in cooler but bright weather.

Potential yields can seem high – but it must be remembered these refer to the maximum possible in-field yield of all fruit. Field yields are generally less and marketable yields less again. Drought in particular may reduce field yields, and this will usually reduce the nutrient demands of the crop.

These recommendations consider two distinct scenarios:

Scenario 1: Potential yield of 40 t/ha. This is representative of mid-season crops with a duration of around 110 days, grown under favourable weather conditions. These crops might achieve 24–32 t/ha of marketable fruit.

Scenario 2: Potential yield 28 t/ha. This is representative of early or late-planted crops that achieve marketable yields around 16–22 t/ha.

For each scenario the recommendations consider an additional variation where the field yield is 80% of potential because of water stress. This is most appropriate for crops where irrigation is not available and water stress is likely because of low rainfall (e.g. on the East Coast of the North Island).

4.2. Nutrients to grow the crop

Buttercup squash responses to N, P and K fertilisers were investigated in the 1980s mostly around Pukekohe (Buwalda 1986, 1987; Buwalda & Freeman 1986; Buwalda et al. 1987). Based on this work King and Wishart (1990) and Wood (1997) have suggested target soil test values for P and K that seem rather high now, especially because the values assumed fertilisers were broadcast or applied in rather wide bands.

Here, the recommendations for N, P, K and Mg are based on a reanalysis of unpublished work carried out in New Zealand from 2000 to 2001 for commercial clients. The cultivar examined was 'Delica', grown at 16 sites in the Manawatu and the Horowhenua. The experiments covered a wide range of combinations of fertiliser rates (applied in bands), and potential yields. Pooled results from these sites were used for fitting the PARJIB model for yield response to nutrient supply (Reid 2002; Reid et al. 2002c). The model accounts for variations in nutrient supply from both the soil and fertilisers. It also accounts for the effects of excessive water on the crop. The model described the field data well. Here, fertiliser recommendations to N and P are calculated using the model to achieve 99% of field yield (potential yield after accounting for the effects of water deficit).

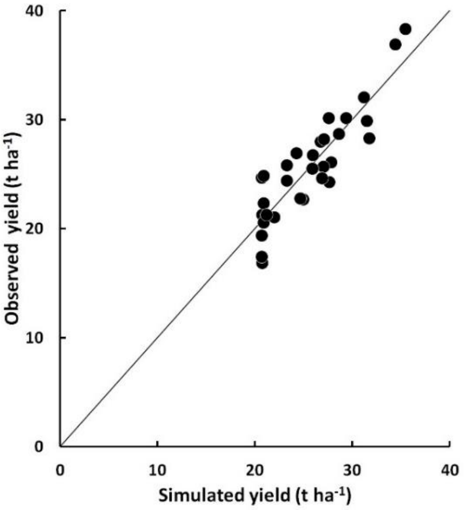


Figure 4-1. Performance of the PARJIB model for buttercup squash. Measured yields are plotted against the simulated values from the model after calibration. The plotted line is the line of perfect agreement.

Soil tests

Before the crop is planted carry out soil testing from 0–15 cm depth *in each paddock*. Choose the standard soil testing suite (pH, Olsen P, QT Ca, K, Mg and Na, CEC and soil volume weight) PLUS 'Available N' (anaerobically mineralisable N, in kg N/ha.

Key point: Assumed soil bulk densities

The generic recommendations for buttercup squash assume the bulk density in the field (ρ_{field}) is 1.1 g/ml and the bulk density of air-dried sieved soil in the laboratory (*volume weight*, ρ_{lab}) is 0.85 g/ml. These values can be used to make the nutrient recommendations below more specific to a site if measured values of ρ_{field} and ρ_{field} are known (see Chapter 2, PARJIB and soil bulk density).

Nitrogen (N)

Buttercup squash can take up considerable amounts of N. Calculations from the results of Buwalda and Freeman (1986) indicate that a crop optimally supplied with N had taken up 82 kg N/ha by 49 days after emergence; by final harvest, at 101 days after emergence, there were 179 kg N/ha in the fruit alone (yield was 38 t/ha of export grade fruit and 50 t/ha of total fruit, at 101 days after emergence). However, the same experiment illustrated that yield can be reduced by excessive N supply (from fertilisers or from mineralisation of N in soils that were recently in pasture). This yield reduction occurs probably because excess N can encourage late-season leaf growth and further flowering at the expense of the fruit that should be approaching harvestable maturity.

If using soluble fertilisers (this includes solid, suspension or dissolved fertilisers), apply half the recommended N just before planting as a band 12–30 cm wide centred on the planting line. Incorporate the fertiliser but not deeper than 12 cm. Side-dress the rest of the recommended N within 2 weeks of crop emergence (around the 2–3 leaf stage and before runners start to form). These applications can be broadcast, but there may be an advantage in applying the N in another band just outside the original banded area or knifing it in about 15–20 cm from the plant line. All side-dressings should be readily available forms like urea.

The N side-dressing at the 2–3 leaf stage can be replaced by **slow- or controlled-release N fertilisers applied at planting**. This may reduce the risk of leaching in wet seasons, but buttercup squash does appear to require a good N supply early in growth. Choose products where the majority of the N becomes plant-available 30–40 days after application, and use these to replace only the side-dressing normally required when using soluble fertilisers; apply them at planting in a band up to 50 cm wide down the planting line. Apply soluble fertilisers as a starter (see above).

If fertigation is available, split the recommended N fertiliser across several applications during crop growth. This can greatly assist in matching N fertiliser supply with the demands of the crop, and lessen the risk of nitrate leaching, but wet weather may restrict the opportunities to apply the fertiliser. Yields may be reduced more by excessive soil wetness than by missing one or two small applications of N.

If using compost sources of N, incorporate these during the cultivations prior to planting.

	Recommended N application (kg N/ha) to grow the crop			
	Scenario 1: Potential yield of 40 t/ha		Scenario 2: Potential yield of 28 t/ha	
Available N (kg N/ha)	No water stress	Water stressed	No water stress	Water stressed
60	180	150	70	20
70	150	110	40	20
80	120	80	20	20
90	90	50	nil	nil
110	30	nil		
120	nil			

These recommendations, based on the PARJIB model, are in accord with earlier recommendations based on experiments conducted in the 1980s (King & Wishart 1990; Wood et al. 1986). However, some growers achieve good results with N applications less than those in the above table.

Nitrogen and squash quality

Inadequate N supply may result in early leaf senescence, letting more direct light into the crop and raising the risk of sunburn on fruit.

Phosphorus (P)

Wood et al. (1986) suggest that a target soil Olsen P value may be as high as 130 for soils around Pukekohe. This appears very high and could encourage excessive applications of P fertilisers. The suggestion appears to be based on experiments where soil Olsen P was changed by applying P fertiliser in a 75 cm wide strip and then incorporating it to 15 cm depth (Buwalda 1986). This appears to be a very inefficient method of supplying P on a soil that has a moderately high ability to fix P. One further reason to be cautious in interpreting Buwalda's results in this way is that of the four nearby sites he studied, yield across all rates of P applied was markedly less at the site with the highest initial soil Olsen P (137 mg/kg).

Key point: Soils that fix P

Wood et al. (1986) state the optimum soil test P is greater on volcanic soils or other soils with a high anion storage capacity (ASC, or P retention %). *There is no good evidence for this in vegetables* – the Olsen P test ranks P supply very well across a wide range of soil types.

But high ASC values *do* restrict the efficiency of P fertilisers – so band soluble P fertiliser as much as possible. This reduces the percentage that is fixed onto soil surfaces.

Recommendations here are based on experiments to fit the PARJIB model (see above), and where fertiliser P was applied in bands up to 30 cm wide.

If using composts, broadcast and incorporate these at least 2 weeks before planting.

If using organic or mineral P fertilisers that are slowly soluble, these can be bulky. Broadcast most of the recommendation before planting, but retain a portion to apply at planting in a band about 25 cm wide centred on the drill line.

If using soluble P fertilisers, apply as much as possible of the recommended P in bands or by knifing it in.

- Knife the P fertiliser in to 5–10 cm depth 10–15 cm from the drill line at planting; or
- Apply it just before planting as a band 12–30 cm wide centred on the planting line, and incorporate the fertiliser to 10–15 cm depth.

Soil Olsen P (µg/mL)	Recommended P application (kg P/ha) to grow the crop			
	Scenario 1: Potential yield of 40 t/ha		Scenario 2: Potential yield of 28 t/ha	
	No water stress	Water stressed	No water stress	Water stressed
10	50	50	30	30
20	40	30	20	20
30	30	20	10	10
40	20	15	11	nil
50	16	nil	nil	
60	nil			

Phosphorus and buttercup squash quality

There is no clear evidence that P supply noticeable affects squash fruit quality in New Zealand.

Potassium (K)

Buwalda (1986) reported that across four sites near Pukekohe yields of buttercup squash declined if soil exchangeable K fell below about 400 mg/kg. This is equivalent to a target QT K value of about 20. Of the four sites Buwalda studied, significant yield responses to fertiliser K were detected at only two, where the initial (unfertilised) exchangeable K was either 120 or 220 mg/kg (corresponding to QT K of about 6 and 11 respectively). At the site with initial QT of about 6, yield responded unambiguously to increasing K applications of up to 300 kg K/ha. At the site with initial QT K of about 11 the treatment receiving no K fertiliser yielded about 33 t/ha, and applying 100 kg K/ha increased yield to about 41 t/ha – but increasing further the K application (up to 300 kg K/ha) had no effect on yield. On that Patumahoe clay loam 100 kg K/ha applied as fertiliser would probably have raised QT K by 1.6–2.5 units (Wood et al. 1986), so from 11 to a maximum of 13.5. This is well short of a target value of 20, and even 300 kg K/ha would have raised it to only 18.5. The absence of yield responses to fertiliser rates >100 kg K/ha at this site then is puzzling and indicates that some caution should be exercised in using a target value based on Buwalda's results.

If using composts, broadcast and incorporate these at least 2 weeks before planting.

If using soluble K fertilisers, apply as much as possible of the recommendation in bands. If K fertiliser is required, apply up to 10 kg K/ha as a starter down the spout or close to the drill line – but avoid scorching germinating seeds. Apply the remainder of the recommendation just before planting as a band centred on the planting line. Make the band 12–30 cm wide and incorporate the fertiliser to 10–15 cm.

	Recommended K application (kg K/ha) to grow the crop			
	Scenario 1: Potential yield of 40 t/ha		Scenario 2: Potential yield of 28 t/ha	
QT K	No water stress	Water stressed	No water stress	Water stressed
2	400	340	280	180
3	380	240	170	70
4	270	130	75	60
5	170	81	nil	nil
6	101	nil		
7	nil			

Potassium and buttercup squash quality

There is a suggestion that K supply during growth has an influence on the incidence of storage rots (Searle et al. 2006). This influence appears complex and depends upon the weather and calcium concentrations in the fruit, so no general recommendation can yet be made.

Calcium (Ca) and lime

Yield responses to fertiliser applications of Ca are very unlikely in New Zealand. There is some evidence that low Ca concentrations in the fruit may increase the incidence of rots during storage (Searle et al. 2006). However, applications of Ca to the soil are very unlikely to affect Ca concentrations in the fruit, as plant water relations and uptake of other nutrients can strongly influence Ca uptake and where in the plant Ca is deposited. Overseas, there is evidence that foliar sprays of Ca compounds may improve shelf life of some cucurbits such as honeydew melon (*C. melo* Inodorus group) but not others such as cantaloupes (*C. melo* Reticulatus group) (Lester & Grusak 2004). There are no data available for the effects of foliar Ca on buttercup squash in New Zealand; however, any the benefits may be rather small because Ca will not be translocated out of leaves into the fruit, and growers usually aim for good canopy cover to avoid sunburn of the fruit. There remains a need to define better if and how storage rots may be avoided by manipulating fruit Ca concentrations.

Calcium is frequently added to the soil in lime applied to raise soil pH. Soil pH appears to have an important influence on buttercup squash yield. Previous recommendations were that soil pH should be kept in the range 5.6–6.8 (Wood et al. 1986) or 6.0–6.4 (King & Wishart 1990). However it is difficult to find an experimental basis for these recommendations. Reanalysis of the experiments used to fit the PARJIB model now suggest that the optimum pH on soils within the Horowhenua and Manawatu is about 6.8. Further research is needed. On the basis of the evidence available:

- Apply lime if pH is less than 6.0, targeting a pH of 6.4–6.8
- Apply fine lime *at least a month before planting.*

Magnesium (Mg)

Experiments on buttercup squash in New Zealand have failed to observe any response in yield or quality to Mg supply from the soil and experiments with Mg fertiliser have not been carried out. Many horticultural soils already contain much exchangeable Mg, and deficiency symptoms in squash are most likely close to maturity when it is too late to correct by fertilisers or foliar sprays. So unless there is clear evidence of deficiency on previous or adjacent crops, Mg fertilisers appear unnecessary.

Sodium (Na), sulfur (S) and trace elements

Do not apply Na fertilisers to buttercup squash in New Zealand. Small amounts of Na present in some compound fertilisers are unlikely to be harmful.

Yield or quality responses to fertiliser applications of S have not been documented in New Zea;and. Soils used for vegetables in New Zealand usually contain adequate quantities of S already; S is commonly applied as part of other fertiliser applications (such as superphosphate or potassium sulfate).

Starter applications of trace elements are unlikely to be economic, unless there is strong evidence of specific deficiencies in previous crops at that site. Maintenance applications are of the order of a few g/ha and availability of these nutrients is so dependent upon pH and changes in soil water content that trace elements applied to the soil can be ineffective. Where a specific deficiency is confirmed by foliar analysis the best option may be to apply a foliar fertiliser as soon as possible at manufacturer's recommended rates. These sprays are best applied in the early morning or evening to extend the drying time and the opportunity for the nutrient to enter the leaves.

4.3. Maintenance nutrient applications

Maintenance applications of any particular nutrient should be made only if none will be applied to grow the crop. For N, maintenance applications should be considered only under organic production systems using composts.

There is comparatively little information available on uptake and partitioning of nutrients within squash crops. There is a great deal of information on nutrients in the fruit flesh, but these may differ considerably from concentrations in the whole fruit. Buwalda and Freeman (1986) presented useful measurements made on a fertiliser experiment near Pukekohe. Some care is needed with their results as there appear to be some inconsistencies amongst the results presented, and no results were presented for nutrients within the vines near harvest, but their data still appears to be the best currently available.

Table 4-1. Typical amounts of N, P and K removed from the soil by buttercup squash crops. The values are recalculated from measurements made on a crop grown near Pukekohe in 1983 (Buwalda & Freeman 1986). These assume that only the marketable fruit are removed from the field.

	N	P	K
kg/t fruit removed from the field	3.7	0.56	3.6
Offtakes (kg nutrient/ha)			
Scenario 1: Potential yield 40 t/ha,			
no water stress, marketable yield 28 t/ha	104	16	101
water stressed, marketable yield 22 t/ha	83	13	81
Scenario 2: Potential yield 28 t/ha,			
water stress, marketable yield 20 t/ha	73	11	71
no water stressed, marketable yield 16 t/ha	58	9	56

Calculate maintenance nutrient applications from the kg of each element *per tonne of fruit removed from the field* (see above table).

A crop yielding 40 t/ha of fruit would have about 40 x 0.56 = 22.4 kg P/ha in the fruit, but not all of this is removed from the field. If 60% of the fruit are removed from the field then the maintenance application of P would be about 40 x 0.56 x 60/100 = 13.4 kg P/ha.

If Olsen P>70, do not apply any maintenance P (allow Olsen P to decrease).

If QT K>10, do not apply any maintenance K.

For methods of application of nutrients follow the guidelines for nutrients to grow the crop.

4.4. Plant analysis

Laboratories may quote typical nutrient concentrations in leaves of buttercup squash using results collated from crops in New Zealand. Comparisons with critical or optimum nutrient concentrations are a better guide to whether a crop is experiencing a nutrient deficiency. However, there is little information available for critical or optimum concentrations. The best information available is from Buwalda and Freeman (1986) (Table 4-2).

Sample the youngest mature leaves or, preferably, whole plants (above ground) about 2 weeks after emergence and compare nutrient concentrations in the dried samples with the values tabulated below. Be very cautious using leaves or plants sampled earlier or later because optimum and critical concentrations of N, P and K will decrease as the plants get larger.

Table 4-2. Critical nutrient concentrations (% dry matter) for buttercup squash 16 days after emergence (Buwalda & Freeman 1986). The values are calculated as the minimum required for the crop to maintain at least 90% of its maximum growth rate.

	Whole plants	Youngest mature leaf
Nitrogen (N)	5.4	7.3
Phosphorus (P)	0.6	0.9
Potassium (K)	5.6	4.4

Most likely nutrient deficiency symptoms

Helpful images are available from the Yara CheckIT app for mobile telephones (Yara 2017). Wood et al. (1986) and King and Wishart (1990) also outline many of the possible deficiency symptoms.

Table 4-3. Possible nutrient deficiency symptoms of buttercup squash grown under New Zealand conditions. The descriptions of symptoms are adapted from those of Wood et al. (1986) and King and Wishart (1990).

Nutrient	Symptoms	Notes
N, nitrogen	Uniform yellowing of the older leaves, lack of vigour	Similar symptoms to S deficiency; be careful that lack of vigour might be due to cool weather
P, phosphorus	Young leaves may be a dull emerald green and expand slowly	
K, potassium	Yellowing of older leaves, marginal scorching	Rarely seen under New Zealand conditions
S, sulfur	Uniform yellowing of the older leaves, lack of vigour	Similar symptoms to N deficiency; be careful that lack of vigour might be due to cool weather
Ca, calcium	Young leaves claw shaped	Unknown in New Zealand
Mg, magnesium	Older leaves yellow beginning at edges, but the veins often remain green	Most noticeable as the crop approaches maturity; few cases of Mg deficiency in butter cup squash crops in New Zealand
B, boron	New leaves distorted, petioles and fruit may crack	Symptoms similar to those of cucumber mosaic virus, but cracks in the petioles are distinctive

4.5. Other cucurbits

There are many other cucurbits grown in New Zealand. The nutrient requirements of these have been studied little. The 1986 Fertiliser Recommendations (Wood et al. 1986) suggest that cucumber, squash and marrow respond similarly to soil P status, but marrow will tolerate lower soil K status. They also suggest marked differences between the species in terms of total N requirements: squash and pumpkins apparently requiring 120–180 kg N/ha, melons, 100 kg N/ha, marrows and courgettes 80 kg N/ha, and cucumber 50 kg N/ha. It is unclear what, if any, was the experimental basis of these comparisons. Furthermore, it is very difficult to predict potential yields for these crops to ease comparisons with recommendations for buttercup squash. Overseas, little distinction is made between the fertiliser requirements of pumpkins and the buttercup, butternut, scallop, acorn, crookneck, straightneck, and zucchini squashes (Basham & Ells 2015; Delahaut & Newenhouse 1997; Motes et al. 2007). However, again it is difficult to find the direct experimental bases for such recommendations.

Until definitive field experiments are carried out on these other cucurbits in New Zealand the best information available suggests:

- For pumpkin (buttercup, butternut), calculate nutrient requirements as per buttercup squash
- For the other cucurbits treat the P and K requirements to grow the crop as per the recommendations for buttercup squash, but assume total N requirements (from the soil and fertiliser combined) will be roughly half of those recommended for buttercup squash.

5 Cabbage, broccoli and cauliflower

These are all varieties of the one species *Brassica oleracea* L., along with Brussels sprouts, kale, collard greens, Savoy cabbage, kohlrabi, and broccoflower. Despite their botanical similarities these crops have important differences in their shape, size and culinary uses. Quality attributes, grading standards, and horticultural management practices can differ substantially between the crops.

Cabbage, broccoli and cauliflower share a crucial agronomic characteristic – often they leave behind a considerable amount of plant residue on the soil surface at harvest. They also share another characteristic – these residues are rich in nutrients.

Key point: Crop residues

If the plants are trimmed at the point of harvest then the trimmings or residues leave on the soil surface a lot of P, K and organic N compounds in particular. This is a resource that can save growers money. The residues are best cultivated back into the soil so that the nutrients can be used by the following crop – and accounted for in the nutrient calculations for that next crop. If this is not done then soil testing for the next crop may not detect the N in the residues – and suggest far too much N is needed for the following crop.

Francis et al. (2003) found that rapid mineralisation of residues from preceding greens crops can lead to large rates of nitrate leaching over winter. This emphases the risks of ignoring the residues from these brassica crops.

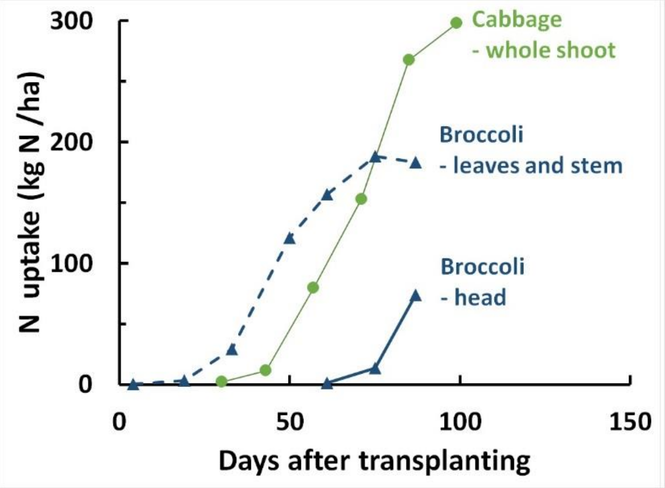


Figure 5-1. N uptake by cabbage and broccoli crops grown near Pukekohe (Sher 1996b). Note that very little N was taken up in the first month after transplanting. Note also that for broccoli 183 kg N/ha (or 71% of the total uptake) was in the leaves and stem – and left behind on the soil surface after harvest. For cabbage the trimmings (30 t/ha) would have left about 75 kg N/ha on the soil surface at harvest (25% of the total uptake).

5.1. Potential, field, and marketable yields

Potential yield has been little studied in these brassicas. In terms of total dry matter production the crops are probably rather similar, but the percentage of that dry matter that goes into the harvestable portion of the plant differs considerably being typically about 80, 18 and 37% for head cabbage, broccoli and cauliflower respectively. Furthermore, the percentage of plants that yield marketable heads or curds is subject to grading standards that vary with marketing requirements and these may change with the time of year.

A further complication is that growers are usually paid on the basis of the number of marketable heads, and this depends on the number of plants as well as the head size or weight.

Nutrient requirements to grow the crops have to be forecast on the basis of field yields (t/ha) before the crop is trimmed and graded – the discarded crop debris still has to grow and use nutrients in order for the marketable material to be grown.

Maintenance applications need to be based on offtakes – the nutrients removed from the field in the marketable product. Again these have to be calculated from measurements or estimates of yields in t/ha.

Key point: t/ha vs heads/ha

If yield is not measured in t/ha then calculate it. This will require some measurement of the average mass of a marketable head (m measured in g), and the number of marketable heads per ha (n). Then yield in t/ha = $m \times n/1{,}000{,}000$ (1,000,000 is the number of grams in a tonne).

Recommendations are given for 6 scenarios, based on the top reported field yields in replicated experiments (Pearson et al. 1999; Prasad et al. 1988; Sher 1996b; Wood 1997), and industry averages (Aitken & Hewett 2016):

1. Cabbage, winter planted, with a marketable yield of 68 t/ha fresh (90 t/ha fresh biomass in field, 25,000–33,000 marketable heads/ha)
2. Cabbage, summer planted, with a marketable yield of 45 t/ha (60 t/ha fresh biomass in field, 25,000–33,000 marketable heads/ha)
3. Broccoli, winter planted, with a marketable yield of 16 t/ha fresh (90 t/ha fresh biomass in field, approximately 33,000 marketable/ha)
4. Broccoli, summer planted, with a marketable yield of 11 t/ha (60 t/ha fresh biomass in field, approximately 33,000 marketable heads/ha)
5. Cauliflower, winter planted, with a marketable yield of 33 t/ha fresh (90 t/ha fresh biomass in field, approximately 28,000 marketable heads/ha)
6. Cauliflower, summer planted, with a marketable yield of 22 t/ha (60 t/ha fresh biomass in field, approximately 28,000 marketable heads/ha).

5.2. Nutrients to grow the crop

Much of the earlier experimental work was carried out at Pukekohe and Levin, but the results are difficult to use because soil N was not measured, some experiments lacked controls, and sufficient experimental details were never published (Webster 1969; Wood 1997).

Norris et al. (2017) measured N uptake of about 320 kg N/ha in summer-planted cabbage that yielded 10 t/ha of shoot dry matter (probably about 100 t/ha fresh mass); fresh yields were probably about 100 t/ha (not reported) but head diameter was about 18 cm. Interestingly, there was no difference in yield between crops receiving 200 and 150 kg N/ha fertiliser. The same authors measured N uptake of about 200 kg N/ha in summer-planted broccoli that yielded 5 t/ha of dry matter; fresh yields were no reported but head diameter was about 10 cm. Interestingly, there was no difference in yield or N uptake between crops receiving 150 and 96 kg N/ha fertiliser.

Prasad et al. (1988) reanalysed responses to phosphorus from the earlier experiments at Levin and this paper remains a valuable resource. Pearson et al. (1999) rescued some of the original experimental files dating back to the early 1960s and carried out a preliminary reassessment for cabbage and cauliflower using the PARJIB model. Their results must be interpreted with caution because potential yield and soil available N had to be estimated during the model fitting process, but responses to P and K supply were apparent.

Given that there is no suitably calibrated model for these crops, recommendations here are based on a combination of the best available information on critical nutrient concentrations in the crops and target soil test values.

Soil tests

Before the crop is planted carry out soil testing for each paddock from 0–15 cm depth. Choose the standard soil testing suite (pH, Olsen P, QT Ca, K, Mg and Na, CEC and volume weight) PLUS 'Available N' (anaerobically mineralisable N, in kg N/ha).

Key point: Assumed soil bulk densities

The recommendations for cabbage, broccoli and cauliflower assume the bulk density in the field (ρ_{field}) is 1.0 g/ml and the bulk density of air-dried sieved soil in the laboratory (*volume weight*, ρ_{lab}) is 1.0 g/ml. These values can be used to make the nutrient recommendations below more specific to a site if measured values of ρ_{field} and ρ_{field} are known (see Chapter 2, PARJIB and soil bulk density).

Nitrogen (N)

Wood et al. (1986) recommended N application rates of 350, 200, and 150–250 kg N/ha, respectively, for winter cabbage, broccoli and cauliflower. Growers have often applied much of the N at planting, with the balance as one or two later side dressings. Williams et al. (2003) working with spinach at Pukekohe showed that such high N application rates at planting are very inefficient and can lead to large amounts of nitrate leaching; it is much better to apply smaller N rates and split them over several applications to better match demands of the crop. Like spinach, these brassica crops take up very little N in the first month after planting (Figure 5-1).The 1986 recommendations were not made without supporting evidence – several New Zealand experiments found these crops can respond to rather high rates of N fertiliser. However, in all cases much of the fertiliser was applied at planting (when crop demand is least and leaching risk highest) and probably much of the N fertiliser was not used by the crop.

For example Pearson et al. (1999) reanalysed a 1969 experiment at Levin using the PARJIB model. That reanalysis suggested cauliflower yield was still responding positively to N fertiliser applications around 300 kg N/ha, but based on the published critical N concentrations (Greenwood et al. 1980a) the required uptake for the top yield would have been around 190 kg N/ha. For cabbage, Wood (1997) and also Pearson et al. (1999) showed yields responding to applications up to 400 kg N/ha when grown through the winter at Pukekohe, but again the likely uptake was much less (around 250 kg N/ha). So in all these cases the continued yield response at high N application rates was probably because a substantial amount of the N applied was lost to leaching as Williams et al. (2003) warned.

Here, the N recommendations are based on critical N concentrations required for the target yield. Only above-ground plant parts are considered. The critical concentrations for cabbage and cauliflower are those reported by Greenwood et al. (1980a), whereas those for broccoli are taken from Appendices 9 and 10 of the UK Fertiliser Manual (Defra 2010). Alternative equations for critical N concentrations have been proposed (Greenwood et al. 1996), but their accuracy and relevance may be difficult to interpret (Riley & Vågen 2003). The recommendations assume no leaching of nitrate below the root zone and the amount of N available from the soil is approximated by the Available N (AMN) test conducted for the top 15 cm of soil. Probably there are errors introduced by both assumptions, but they will tend to compensate for each other.

It is important to note that if the target yield is substantially different from specified in the scenarios (Section 5.1) then the recommended fertiliser rates must be adjusted in simple proportion. For example in Table 5-1 the assumed target yield for summer-planted broccoli is 11 t/ha. If the target yield is 19 t/ha for any soil available N value the recommended N fertiliser rate will be (19/11) times the value in the table.

At planting:

- Soluble and controlled release N fertilisers are best incorporated or knifed in 2–5 cm from the plant row.
- **If using only soluble N fertilisers** like urea, ammonium sulfate, or CAN, apply no more than 20 kg N/ha, or up to 50 kg N/ha if this is a winter-planted crop and wet weather will greatly limit opportunities for side-dressing in the second and third months of growth.
- **If using controlled release N fertilisers,** apply up to 100 kg N/ha of the controlled release product and up to 20 kg N/ha of a soluble N fertiliser.

Split the remainder of the recommended N across at least two side-dressings after the plants have at least two true leaves (direct seeded crops) or have grown two extra leaves after transplanting. Avoid applying more than 50 kg N/ha at any one time. Side-dressings may be broadcast (if possible just before light rain or irrigation) but be careful to avoid fertiliser lodging amongst the leaves where it can cause cosmetic damage.

If applying N in the form of composts then incorporate these at least 2 weeks before planting.

Table 5-1. Recommended total N fertiliser rates (kg N/ha) for cabbage, broccoli and cauliflower scenarios. If the target yield is substantially different from specified in the scenarios (Section 5.1) then adjust the recommended fertiliser rates in simple proportion. For example, if the target yield for summer-planted broccoli is 20 t/ha compared with the scenario yield of 11 t/ha, and the soil available N is 50 kg N/ha, then the recommended N fertiliser rate is 70 x 20 /11 = 122 kg N/ha.

Soil Available N (kg N/ha)	1 Cabbage, winter planted	2 Cabbage, summer planted	3 Broccoli, winter planted	4 Broccoli, summer planted	5 Cauliflower, winter planted	6 Cauliflower, summer planted
50	195	115	125	70	230	135
90	155	75	85	30	190	95
130	115	35	45	nil	150	55
170	75	nil	nil		110	15
210	35				70	nil
250	nil				30	
290					nil	

Wood et al. (1986) suggested total nitrogen requirements for winter cabbage, summer cabbage, cauliflower, and winter broccoli are 350, 150–200, 150–250, and 200 kg N/ha respectively. It seems that in practice these are sometimes interpreted as fertiliser N requirements, ignoring supply from the soil, which is no longer acceptable or justified. If soil supply is taken into account then Wood et al.'s figures are in good agreement with the values in the above table except for the winter crops where Wood et al. recommended applying surplus N to compensate for the risk of nitrate leaching. This is inconsistent with the Code of Practice for Nutrient Management (Section 1.4).

N and crop quality

Adequate N supply is important to maintain good leaf colour. Excessive N fertiliser, though, can lead to problems with N leaching in season and afterwards (as the crop residues break down). A combination of very high N fertiliser rates and dull weather can raise nitrate concentrations in the edible plant portions, but the reported concentrations in these crops are rather less than in lettuce and spinach and there is no indication that the values are of concern for human health (Santamaria et al. 1999; Thomson et al. 2007).

In the UK, applying less or more than optimum applications of N can lead to excessive production of immature terminal shoots (Greenwood et al. 1980b). Furthermore, applying more than the optimum N to broccoli increases the risk of head or spear rot (due to *Pseudomonas* and *Erwinia* species) (Everaarts 1994). Excessive N fertilisation can result in a smaller dry matter percentage in cabbage, which is usually a negative quality attribute, and it can also cause yellowing in cauliflower curds (Greenwood et al. 1980b).

If harvest must be delayed, and experience indicates there is a risk of leaf yellowing because the crop is mature, then a light foliar application of N may help maintain leaf condition. The best rates have not been identified experimentally, and concentrated solutions risk leaf scorching, so it is probably best to limit individual applications to <5 kg N/ha. *If leaf yellowing has already begun then foliar N applications will not reverse it*, and may not slow it noticeably over periods of 1 or 2 weeks. For broccoli and cauliflower it is important to avoid applying too much N in this way because that may cause other quality issues (see above).

Phosphorus (P)

For cabbage, broccoli and cauliflower, target Olsen P values varying from 35 to 75 ppm have been reported (Prasad et al. 1988; Wood et al. 1986), but experimental evidence has been published only for values around 40 ppm. Results from the modelling analysis of Pearson et al. (1999) imply a target Olsen P around 40–50 ppm for cabbage and cauliflower. All those target values assume fertiliser P is broadcast. We must assume that broccoli responds to P supply similarly to cabbage and cauliflower.

If Olsen P<45 µg/mL then apply sufficient P fertiliser to raise the Olsen P to 45. The rate depends on the soil type and can be calculated using the rules in Chapter 2 *(*To raise soil Olsen P).

- Reserve up to 20 kg P/ha of this total to apply as a starter fertiliser. If direct seeding, apply the fertiliser down the spout if this enables some separation of seed and fertiliser, alternatively knife the starter P in as a narrow band 2–5 cm from the plants.
- The remainder of the recommendation should be applied as a capital or base dressing before planting. This fertiliser should be broadcast and incorporated to 15 cm depth.

P and crop quality

There have been few reports of P supply affecting the quality of these crops. Greenwood et al. (1980c) noted that in one experiment increasing P supply appeared to reduce the incidence of stem rot in cabbage.

Potassium (K)

Previous recommendations (Wood et al. 1986) identified target QT K values ranging from 8 in sand through to 15 in clays, assuming the K was broadcast. There were no published experimental data relating performance of these crops to soil QT K or even to exchangeable K concentrations, so it is difficult to appraise what those previous recommendations were based on, and the basis for distinguishing target K concentrations on the basis of soil texture. However, the reanalysis of Pukekohe and Levin experiments by Pearson et al. (1999) suggests that yield will respond gradually to broadcast K fertiliser provided the QT value is less than 15, although the responses may not be economic at QT values >10.

If QT K <12 then apply sufficient K fertiliser to raise QT K to 12. The rate depends on the soil type and can be calculated using the rules in Chapter 2 (To raise soil QT K).

- Reserve a portion of the total to apply as a starter fertiliser. SOP will be safer to use for this than MOP. If direct seeding, apply up to 15 kg K/ha down the spout provided there is some separation of seed and fertiliser. Alternatively, knife in up to 30 kg K/ha as a narrow band 2–5 cm from the seed.
- The remainder of the recommendation should be applied as a capital or base dressing at least 4 weeks before planting. Broadcast and incorporate it to 15 cm depth. Use the cheapest form of K fertiliser you have available (usually MOP).
- Try to avoid surplus K supply to the crop because this can encourage clubroot infections (Donald & Porter 2009).

Potassium and crop quality

Greenwood et al. (1980d) reported that in one UK experiment excessive supply of K increased stem rot in cabbage, but sub-optimum supply of K to cauliflower severely increased the incidence of defects in the curds (yellowing, bracted or loose curds). That apart, there seem to be few issues associated with K supply and quality in these crops.

Magnesium (Mg) and sodium (Na)

There is no evidence that in New Zealand yield of the cabbage, broccoli or cauliflower will respond to fertiliser applications of Mg, Na, or S. Taste of the leaves in particular might by affected by luxury uptake of these nutrients, but there have been no New Zealand studies that we are aware of. It will be a sensible precaution to apply a foliar spray of Mg at manufacturer's recommended rates *if there have been clear visual symptoms of Mg deficiency in previous brassica crops at the same site*. The symptoms are mainly pale colours between the veins of the older leaves.

Sulfur (S)

There is no indication that deficiency of S affects yields of these crops in New Zealand and S supplements for crops cannot be recommended for improving yields. Much S is applied to crops indirectly in other fertilisers like superphosphate and potassium sulfate. Luxury uptake of S in particular may be quite large, and S is an important component of many of the chemical compounds associated with taste and health attributes of these brassica crops (Engel et al. 2002; Freeman & Mossadeghi 1972; Hansen et al. 1997). In terms of flavour and consumer acceptance, the situation is quite complex, and increasing plant uptake of S can have both positive and negative influences. So it is possible that with some local knowledge crop quality could be adjusted by varying S applications.

Calcium (Ca) and lime

Yield and quality responses to Ca applications are unlikely in New Zealand as most horticultural soils contain an excess of this nutrient already.

Apply lime if pH is less than 6, targeting a pH of 6.5.

There is considerable uncertainty about this target pH. Clubroot disease (*Plasmodiophora brassicae* Woronin) can be devastating to yields and generally the incidence and severity of this disease is reduced at pH 7.2, but raising the soil pH to this value will not necessarily control the disease and may decrease yields (Donald & Porter 2009; Nott et al. 1994). If clubroot is likely to be a problem in the paddock then probably it is better to attempt control through an integrated use of resistant cultivars, fungicides, and lime rather than rely on soil pH control alone. Maintaining pH values this high may induce trace element deficiencies in the crop (see below) and in subsequent crops of different species. There have been no definitive experiments measuring yield response of vegetable brassicas to soil pH values in the absence of clubroot, but there are indications that the pH for maximum yield is less than that required to control clubroot (Nott et al. 1994).

Trace elements

In general, applications of trace elements to these crops are unlikely to generate an economic return, unless there is strong evidence that specific deficiencies have occurred on previous crops at that site. Offtakes are of the order of a few g/ha and availability of these nutrients is so dependent upon changes in soil aeration (water content) and pH that fertiliser applications to the soil will often be wasted.

In the UK, molybdenum (Mo) deficiency can be a problem for cauliflower on acid soils. Symptoms include restricted growth of the leaf lamina ('whiptail'). Following the recommendations below for lime should mean this problem does not occur. If soil pH has been raised above 6.5 to help control clubroot then deficiencies of Cu, Zn, Fe and Mn may occur. There is evidence that an adequate supply of B is helpful in the control of clubroot

(Donald & Porter 2009), but there appears to be no field evidence relevant to New Zealand conditions that could be used to formulate a safe recommendation

If trace element deficiencies do occur the best option may be a foliar spray at the manufacturer's recommended rates. Foliar sprays are best applied in the early morning or evening to extend the drying time and the opportunity for the nutrient to enter the leaves.

5.3. Maintenance nutrient applications

Representative concentrations of nutrients in cabbage, broccoli and cauliflower are given in Table 5-2.

Table 5-2. Concentrations (kg nutrient per tonne of yield) of N, P, K, S, Ca and Mg in cabbage, broccoli and cauliflower. Data for cabbage and broccoli are for New Zealand crops grown near Pukekohe (Sher 1996b). The cauliflower data are taken from the USA (USDA 2018).

	N	P	K	S	Ca	Mg
Cabbage (whole shoot)	2.5	0.28	2.1	1.1	3.3	0.17
Broccoli (leaves and stems)	2.8	0.42	4.2	0.77	2.2	0.14
Broccoli (head)	4.1	0.62	3.3	0.77	0.28	0.13
Cauliflower (head)	4.0	0.61	2.9			

Maintenance nutrient applications can be estimated by multiplying the expected or measured yield (t/ha) by the concentrations in Table 5-2 (kg nutrient per tonne of product removed from the field). Representative offtakes calculated in this way are given in Table 5-3.

Table 5-3. Calculated offtakes (kg/ha) of N, P, K, S, Ca and Mg from crops of cabbage, broccoli and cauliflower. Data are based on Table 5-2, and assumes that only the marketable yield is removed from the field.

	Marketable yield (t/ha)	N	P	K	S	Ca	Mg
Cabbage, winter planted	68	169	19	142	71	223	11
Cabbage, summer planted	45	113	13	95	47	149	8
Broccoli, winter planted	16	67	10	53	13	5	2
Broccoli, summer planted	11	45	7	35	8	3	1
Cauliflower, winter planted	33	134	20	98	0	0	0
Cauliflower, summer planted	22	90	13	65	0	0	0

- For methods of application of maintenance nutrients follow the guidelines for nutrients to grow the crop.
- Maintenance applications of any particular nutrient should be made only if none will be applied to grow the crop. For N, maintenance applications should be considered only under organic production systems using composts.
- If Olsen P>50, do not apply any maintenance P (allow Olsen P to decrease).
- If QT K>15, do not apply any maintenance K.

5.4. Plant analysis

Typical leaf or whole-plant nutrient concentrations are of little use here. Wood et al. (1986) presented critical N, P and K concentrations for different aged plants of cabbage and cauliflower, but not broccoli. They did not cite the sources of the information. Critical nutrient concentrations vary with plant mass not plant age as such – variations in weather and planting densities make the values cited by Wood et al. difficult to use. Suitable information on critical N, P and K concentrations is available from the UK for cabbage and cauliflower, but again there appear to be no separate measures of critical P and K concentrations for broccoli.

Recommended values to use are in Table 5-4. These are useful benchmarks for diagnosis of N, P and K deficiencies. If plant analysis indicates values below the ranges given here, then there is a substantial risk the crop is suffering from a nutrient deficiency.

Table 5-4. Critical concentrations of N, P, and K in whole plants of cabbage, broccoli and cauliflower. Values are given as % dry matter (DM). Values for cabbage and cauliflower are from Greenwood et al. (1980a) and those for broccoli are taken from Appendices 9 and 10 of the UK fertiliser recommendations Defra (2010). Plant fresh mass is estimated from dry mass, assuming dry matter percentages of 10.9, 7.8, 10.0, and 10.0 respectively for winter cabbage, summer cabbage, summer cauliflower and broccoli.

	Plant mass (g/plant)		Critical nutrient content (% DM)		
Crop	dry	fresh	N%	P%	K%
Winter cabbage	4.2	38	4.9	0.48	3.2
	10	92	4.7	0.49	3.0
	100	917	4.2	0.50	2.9
	164	1503	3.8	0.52	2.6
	125	1142	3.2	0.53	2.5
Summer cabbage	0.3	4	5.2	0.58	4.8
	7.2	92	5.1	0.55	4.3
	10	128	4.9	0.50	4.0
	100	1282	3.8	0.44	3.0
Summer cauliflower	0.2	2	5.9	0.58	3.8
	2.7	27	5.2	0.54	3.4
	10	100	5.0	0.51	3.3
	76	760	4.1	0.45	3.0
	100	1000	3.8	0.40	2.6
Broccoli	4	40	4.2		
Broccoli	10	100	2.4		
Broccoli	100	1000	1.9		
Broccoli	160	1600	1.9		

Most likely deficiency symptoms

See Table 5-5. Excellent images of these were published by Scaife and Turner (1983). Helpful images are also available from the Yara CheckIT app for mobile telephones (Yara 2017).

Table 5-5. Nutrient deficiency symptoms of cabbage, broccoli, and cauliflower grown in the field under New Zealand conditions. The descriptions of symptoms are adapted from those of Wood et al. (1986).

Nutrient	Symptoms	Notes
N, nitrogen	Bronze, pink or purple colours in the foliage; early yellowing and senescence of the older leaves	Bronze, purple and pink colours may be caused by several other factors, and are sometimes cultivar characteristics Excessive N supply can cause hollow stems (and branches of the head), and very small flower buds that give cauliflower and broccoli heads a fuzzy appearance
P, phosphorus	Muddy purple colours in old leaves, red curd in cauliflowers	
K, potassium	General reduction in growth; bronzing on the leaf edges, followed by death of tissue around the leaf edges and then between the veins	Rarely seen under New Zealand conditions, except perhaps on shallow sandy soils, but moderate K deficiency shows few visual symptoms and can restrict yields
S, sulfur	Primary and secondary veins form a blue-green pattern against pale green background	Rarely seen in New Zealand crops, perhaps because many commonly used P and K fertilisers contain S also
Mg, magnesium	Pale colours between the veins of older leaves, red tints may follow	No verified cases of Mg deficiency in New Zealand
Mo, molybdenum	Leaves may be strap-like and crinkled, in severe cases only the leaf ribs develop and head formation is stopped	Cauliflowers most susceptible ('whiptail'); may be associated with low soil pH
Zn	Cabbage leaves cupped without-curved margins	Generally associated with high soil pH
B	Stems become hollow, cauliflower curds turn brown	Many New Zealand soils may be borderline in B supplying ability, but B toxicity is easily induced by over-zealous application of B; *hollow stems are also caused by excessive N supply*

6 Carrots

Carrots for the fresh market are grown throughout New Zealand, although carrots for processing are grown mostly in Canterbury, the Manawatu and Hawke's Bay. Carrot nutrient requirements depend greatly on potential yield – the total fresh yield of roots in the field if there is no water or nutrient stress.

6.1. Potential yields

Potential yield in carrots typically varies from about 70 to 170 t/ha. Most crops do not reach their potential because of water or other stresses, and field yields vary from about 50 t/ha for table carrots to 120 t/ha for process carrots.

Unlike most other crops, potential yield of carrots depends mainly on the plant population and the target root size (dictated by the intended end-use). Baby carrots are planted for population densities up to 1500 plants/m^2. Processing carrots have populations typically around 50 plants/m^2. Between these extremes, table carrots typically have populations of 70 plants/m^2.

Usually the crop is left to grow until the target root size is achieved or the market or processor is ready for the crop. Unless frosts, pests or diseases affect plants, *water and nutrient stresses will mainly have the effect of slowing crop growth*. The main benefit of good nutrient supply is that the crop will grow quickly, reducing the risk of autumn frosts stopping growth before the target root size is reached. Partly because of this, and partly because they have a deep fine root system (Figure 6-1), carrots have a reputation of being unresponsive to fertiliser. Nevertheless they take up large amounts of nutrients and fertilisers can be beneficial when potential yields are high.

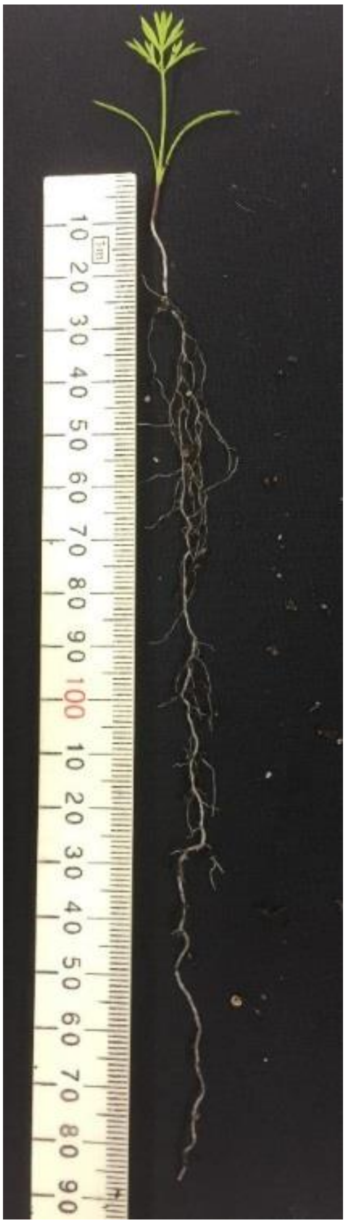


Figure 6-1. Root system of a carrot plant 17 days after planting. The depth scale is 0–190 mm. Photograph by Jeff Reid 2018.

Nutrient recommendations are given for two contrasting scenarios.

Scenario 1: Potential yield of 100 t/ha. This is appropriate for many crops of fresh market carrots where marketable yields may be 70–90 t/ha. It is towards the top-end for well-managed baby carrots.

Scenario 2: Potential yield of field 170 t/ha. This is realistic for process carrot crops if weather conditions are good and the crop is well managed – marketable yields may be up to 150 t/ha (Hunt et al. 2015; Hunt et al. 2016; Johnstone et al. 2014; Reid & English 2000).

6.2. Nutrients to grow the crop

The recommendations for N, P, K and Mg are based on work carried out with the variety Carson at 7 different sites in New Zealand from 2013 to 2016. The experiments covered a wide range of combinations of fertiliser rates, potential yields, and planting densities. The results from all sites were collated and analysed together by fitting the PARJIB model (Reid 2002; Reid et al. 2002c). The model fitted the data well and very similar calibrations were obtained in earlier years for both Koyo carrots and the variety Chantenay Red Core. Furthermore, the model's predictions for P responses match well with the independent observations of Prasad et al. (1988).

Yield response to N, P and K supply is very gradual unless the soil test values are unusually low. Here, fertiliser recommendations are calculated to achieve 99% of potential yield.

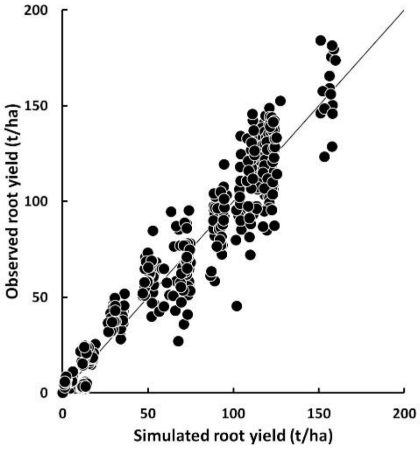


Figure 6-2. Performance of the PARJIB model for process carrots. Measured yields are plotted against the simulated values from the model after calibration. The plotted line is the line of perfect agreement. A root yield of 150 t/ha corresponds to 19.5 t/ha dry yield.

Despite their deep root system carrots are very sensitive to water stress; high yields and quality will not be achieved if the crop is water stressed or over-watered (Reid & Gillespie 2017). Similarly, water stress will suppress the crops responsiveness to nutrient applications.

Soil tests

Before the crop is planted in each paddock carry out soil testing at TWO depth ranges:

1. **0–15 cm depth** – standard soil testing suite (pH, Olsen P, QT Ca, K, Mg and Na, CEC and soil volume weight) PLUS 'Available N' (anaerobically mineralisable N, in kg N/ha).
2. **0–60 cm depth** – mineral N test (nitrate plus ammonium, in kg N/ha).

Key point: Assumed soil bulk densities

The recommendations for carrots assume the bulk density in the field (ρ_{field}) is 1.0 g/ml and the bulk density of air-dried sieved soil in the laboratory (*volume weight*, ρ_{lab}) is 0.9 g/ml. These values can be used to make the nutrient recommendations below more specific to a site if measured values of ρ_{field} and ρ_{field} are known (see Chapter 2, PARJIB and soil bulk density).

Nitrogen (N)

Yield response to N fertiliser is slight unless the supply of N from the soil is small (Reid et al. 2017). Fertiliser applications >150 kg N/ha are rarely economic because the crop is very effective at scavenging N mineralised from organic matter in the soil.

If using composts or slow-release fertilisers broadcast and incorporate these at least 2 weeks before planting.

If using soluble N fertilisers split recommendations >50 kg N/ha into at least two broadcast applications. Apply one at sowing or just after the crop has established, and the rest when the plants have at least six true leaves.

If fertigation is available, split the recommended N fertiliser amount across several smaller applications from emergence to about a month before harvest.

N recommendations are based on the **sum** of Available N from 0–15 cm and mineral N from 0–60 cm depth.

Sum of Available N and mineral N (kg N/ha)	Recommended N application (kg N/ha) to grow the crop	
	Scenario 1: Potential yield 100 t/ha	Scenario 2: Potential yield 170 t/ha
50	100	210
100	50	150
120	20	130
150	nil	100
190		50
210		up to 20
>240		nil

Phosphorus (P)

P fertiliser is normally broadcast for carrots. Separate calibrations for the PARJIB model had been made for high and low ASC soils (Hunt et al. 2016; Pearson et al. 2004) where P was broadcast. A comparison of these calibrations indicates rather lower efficiency of broadcast P fertiliser when ASC is high. This strongly suggests that in high ASC soils banding of P fertiliser will improve the efficiency of its use.

Base or maintenance dressings can be broadcast. However, any P fertiliser applications required to increase yield are best split with up to 20 kg P/ha applied as a starter (either down the spout or banded 2–5 cm from the drill line). The rest can be broadcast on soils with ASC less than about 30%, and banded close to the drill lines on soils with higher ASC. Only side-dress growing crops with P if it is early in the life of the crop so that the roots have time to access the P.

	Recommended P application (kg P/ha) to grow the crop	
Soil Olsen P (µg/mL)	Scenario 1: Potential yield 100 t/ha	Scenario 2: Potential yield 170 t/ha
10	30	70
15	30	60
20	25	50
30	nil	40
40	nil	nil

Potassium (K)

In New Zealand it has proven hard to detect carrot yield responses to K fertiliser (Hunt et al. 2015; Hunt et al. 2016). However, the reanalysis carried out for these recommendations suggests that sometimes when comparing different sites yields may correlate with soil QT K values. This might be an indirect association: soil types with low QT K tend to be sandy and drought-prone. Within sites there is rarely any such correlation.

- It is recommended that you do not apply K fertiliser to grow the crop.
- However, maintenance applications are suggested (see below).

Magnesium (Mg)

Additions of Mg from fertilisers or composts are unlikely to benefit carrots in New Zealand. When fitting the PARJIB model for carrots it became apparent that in experiments in Canterbury, Hawke's Bay, and Ohakune, soil Mg QT values from 13 to 43 had no relationship to yield. Maintenance applications are not recommended unless QT Mg <20.

Sodium (Na)

Carrots are unusual in that they may respond to Na fertilisers (usually salt, NaCl) when K supply is poor (Cooke 1982). Carrot crops can remove quite large amounts of Na (see above) but if K supply is adequate, Na fertilisers can be omitted.

Sodium fertilisers can have undesirable effects on soil structure, but applications of <50 kg Na/ha incorporated before planting are unlikely to be detrimental in New Zealand.

Calcium (Ca) and Sulfur (S)

Direct responses to applications of Ca or S are very unlikely. Such responses have not been observed in New Zealand because the soils mainly used for carrots usually contain large amounts of Ca and S already. Both elements are commonly applied in other fertilisers (e.g. lime and superphosphate).

Lime requirements

In Europe, carrots sometimes react badly to lime applied shortly before planting. Soil pH values as low as 5.2 do not appear to affect yield in New Zealand, but values appreciably above 6.5 may cause trace element deficiencies. Cavity spot (*Pythium coloratum*) disease of carrot roots is often reduced by lime applications – this seems to be a direct effect of raising soil pH not of the Ca in the lime (El-Tarabily et al. 1997). However, the optimal soil pH for cavity spot control is not known in New Zealand, and if cavity spot has been a problem before it may be most practical to plant your carrots elsewhere.

Apply fine lime at least a month before planting and only if pH is less than 5.3, targeting a pH of 5.8–6.0.

Trace elements

Applications of trace elements to New Zealand carrot crops are very unlikely to generate an economic return, unless you have strong evidence from previous crops that specific deficiencies have occurred. Maintenance applications are tiny (see below) and availability of these nutrients is so dependent upon changes in soil aeration (water content) and pH that fertiliser applications to the soil will usually be wasted. Potential exceptions could be boron following a wet winter and spring, and copper on organic soils. If B or Cu deficiency have been observed in previous carrot crops at the site, then the best option may be a foliar fertiliser at the manufacturer's recommended rates. These are best applied in the early morning or evening to extend the drying time and the opportunity for the nutrient to enter the leaves.

6.3. Maintenance nutrient applications

Maintenance applications of any particular nutrient should be made only if none will be applied to grow the crop. For N, maintenance applications should be considered only under organic production systems using composts.

Carrots have a marked tendency for luxury uptake – they will continue to take up some nutrients beyond the amounts needed for maximum growth. The surpluses are stored in the storage roots. Table 6-1 below show the approximate amounts of mineral nutrients that can be removed from the soil by carrot crops in New Zealand. Nutrients in the shoots are usually returned to the soil after harvest.

Table 6-1. Typical amounts of nutrients removed from the soil by a carrot crop yielding 100 t/ha (13 t DM/ha). The values are calculated from 13 crops sampled in 2013–14 (Johnstone et al. 2014). The nutrients in the storage roots are removed from the paddock, the rest are recycled when the crop residues are incorporated.

	N	P	K	S	Ca	Mg	Na	Fe	Mn	Zn	Cu	B
Shoots (kg/ha)	67	6	80	17	89	11	49	3.1	0.5	0.2	0.1	0.2
Storage roots (kg/ha)	174	31	288	16	33	12	64	2.0	0.2	0.7	0.1	0.3
Total uptake (kg/ha)	241	37	368	33	123	23	113	5.1	0.7	0.9	0.2	0.4

Maintenance applications should be calculated from the kg of each element taken up per tonne of roots *removed from the field* (see Table 6-2). This is not necessarily the marketable yield reported to a grower by the processor. If 100 t/ha of roots are removed from the field then the maintenance P application is about 100 x 0.31 = 31 kg P/ha in the roots.

Table 6-2. Offtakes of the major nutrient calculated for scenarios 1 and 2. These values assume that 80% of the potential yield is removed from the field. That percentage will vary between crops.

	N	P	K	S	Ca	Mg	Na
kg/t roots	1.74	0.31	2.88	0.16	0.33	0.12	0.64
Offtakes (kg/ha)							
Scenario 1, pot. yield 100 t/ha	139	25	230	13	26	10	51
Scenario 2: pot. yield 170 t/ha	237	42	392	22	45	17	87

For methods of application of P follow the guidelines for nutrients to grow the crop. If Olsen P>55 then do not apply any maintenance P (allow Olsen P to decrease).

Solid K fertiliser should be broadcast and incorporated before planting. Use the cheapest source available. Large rates of MOP left on the soil surface may reduce plant populations, affecting yield and quality (Hunt et al. 2015). Recommended rates of either MOP or SOP incorporated pre-sowing are unlikely to affect crop yield or quality.

Maintenance K applications are not always necessary. There is little chance of these being profitable, and sedimentary soils in New Zealand already contain much K – serious depletion of these reserves by the occasional carrot crop is unlikely. Also the figures available for K removals probably reflect luxury uptake – forever replacing these removals would encourage further unnecessary uptake.

The maintenance recommendations here follow the strategy (a) If QT K<15 then apply half the calculated amount for the potential yield; (b) Check the soil QT K at least a month before the following crop, (c) Apply further K fertiliser if the new QT value appears limiting for the next crop.

If QT K>15 then do not apply any maintenance K.

If QT Mg>19 then do not apply any maintenance Mg.

6.4. Plant analysis

Laboratories may quote typical nutrient concentrations in leaves and roots of carrots using results collated from crops in New Zealand. These can be a poor guide to the nutritional status of any specific crop because carrots have a strong capacity to uptake luxury amounts of mineral nutrients. The critical concentrations required for maximum growth rates are usually rather lower. The critical N and K concentrations decrease with age and plant mass. According to Greenwood et al. (1980a), for very young plants the critical concentrations (in the whole plant) are about 4, 0.35 and 4% for N, P and K respectively. By the time the plant dry mass is 40 g (harvest time for many table carrots) these values are about 2, 0.35, and 2%. The values of N_{crit} estimated by Greenwood et al. may be too high for some situations (Reid et al. 2017; Sorensen 1999). The values for K_{crit} also seem high.

Piggot (1986) collated critical nutrient concentrations from a variety of earlier sources (Table 6-3). Unfortunately the ages and plant masses were not given. For N, P and K it appears better to use critical values interpolated from Figure 1 of (Greenwood et al. 1980a) (Table 6-4). For young crops sample the whole shoot. If the crop is close to harvest then sample separately the youngest mature leaves and the storage roots. By that time it is too late to affect the nutrition of that crop, but the results may be useful for managing future crops.

Table 6-3. Critical nutrient concentrations for carrots compiled from various sources by Piggot (1986). Values are given on a dry mass basis.

Nutrient		Young plants Whole shoot	Mid-growth Youngest mature leaf	Around harvest Youngest mature leaf	Around harvest Storage root
Nitrogen (N)	%	3.5–3.7	1.8	1.5	0.8
Phosphorus (P)	%	0.35–0.44	0.18	0.2	0.3
Potassium (K)	%	3.5–3.7	2.0	1.0	1.3
Calcium (Ca)	%			1.8–2.0	0.30–0.35
Magnesium(Mg)	%		0.15		
Copper (Cu)	ppm		4.0		
Zinc (Zn)	ppm		18		
Boron (B)	ppm		20		

Table 6-4. Critical nutrient concentrations for carrots from the field experiments of (Greenwood et al. 1980a). Values are given on a dry mass basis. The assumed dry matter (DM) % for shoots and roots was 10%.

	Dry mass (g/plant)	Fresh mass (g/plant)	Critical nutrient content (% DM) N%	P%	K%
Storage root	0.2	2	2.4	0.31	2.5
Storage root	6.1	61	2.2	0.34	2.3
Storage root	24.0	240	2.0	0.33	2.1
Shoot	0.4	4	3.2	0.35	3.9
Shoot	2.4	24	2.6	0.39	2.9
Shoot	8.0	80	2.0	0.34	1.9

Most likely deficiency symptoms

Visual symptoms of nutrient deficiencies are rare in carrots grown in New Zealand.

Excellent images of deficiency symptoms were published by Scaife and Turner (1983). Helpful images are also available from the Yara CheckIT app for mobile telephones (Yara 2017), although the accompanying descriptions are sometimes at odds with New Zealand experience of where such deficiencies may occur. Wood et al. (1986) also outline many of the possible deficiency symptoms.

Table 6-5. Nutrient deficiency symptoms of carrots grown in the field under New Zealand conditions. The descriptions of symptoms are adapted from those of Scaife and Turner (1983) and Wood et al. (1986).

Nutrient	Symptoms	Notes
N, nitrogen	Uniformly pale green/yellow with fine leaflets	
P, phosphorus	No yellowing, old leaves purple	Some high carotene varieties may have purpling without P deficiency; similar symptoms from carrot fly attack, distinguished by there being gnawing damage to the storage roots – carrot 'motley dwarf' virus also reddens older leaves but younger leaves are yellow
K, potassium	Old leaves scorch and collapse; later, entire petioles of these leaves look water-soaked, then dry up and collapse	Severe deficiency rarely seen under New Zealand conditions, except perhaps on volcanic or shallow sandy soils with soil test K<12; moderate K deficiency shows few visual symptoms and can restrict growth rates
S, sulfur	New leaves uniform yellow colour	Rarely seen in New Zealand crops, perhaps because many commonly used P and K fertilisers contain S also
Ca, calcium	Dead tips of new leaves and growing point; short lengths of water-soaked area on the petioles, leading to collapse of leaf while still green	Extremely unlikely as New Zealand soils have ample available Ca
Mg, magnesium	Older leaves yellow beginning at edges; red tints move in from margins – some backward curling of leaflets may occur	No verified cases of Mg deficiency in carrot crops reported in New Zealand; easily confused with N deficiency and carrot 'motley dwarf' disease
Cu, copper	Youngest leaves become very dark green and fail to unfold; older leaves appear wilted	May be associated with high soil pH, but most serious on peats regardless of soil pH
B, boron	Leaflets of young leaves very small and die back; older leaves may be yellow with purple edges and curl backwards so plant appears prostrate – storage roots split, exposing the core which may have cavities, root surface is dull and greyish	Splitting may be caused by several other factors, including sudden changes in soil water content
Zn, zinc	Symptoms specific to carrots have not been described; on basis of other crops expect very small leaves that may be malformed and turn yellow to white	Carrots have low sensitivity to Zn deficiency, although it is common in California; most likely associated with high soil pH or organic soils

7 Lettuce

Lettuce (*Lactuca sativa* L.) for the local market is grown throughout New Zealand under a wide range of soil and weather conditions. In regions such as Pukekohe, Poverty Bay and the Horowhenua it is grown intensively, sometimes with multiple crops per year on the same ground – this increases the importance of ensuring optimal nutrient supplies for each crop.

Lettuce yields need to be thought of in terms of the shoot biomass (total above-ground growth), the marketable mass of the crop, and the number of marketable heads. The marketable mass is often about 50% of the shoot biomass, but that percentage can vary greatly according to the marketing requirements and the condition of the crop. Grading standards for fresh-packed heads can be very strict and packouts can vary from zero to almost 100% of the plants in a field. Experience with fertiliser experiments in New Zealand is that provided the soil is not especially infertile the percentage of biomass production that goes into marketable yield is often unresponsive to fertilisers.

7.1. Potential and field yields

The potential biomass yield is dictated mainly by plant population (plants/ha), plant variety and type of lettuce (e.g. head, leafy, frilly), and target plant or head size. Weather conditions affect the growth rate, and usually harvest must wait until the heads reach the target size. If the nutrient supply is not optimal then the crop may take longer to reach that stage, which might affect quality but not field yield. If the nutrient supply is more than optimal the crop cannot grow faster than the weather conditions allow.

Some crops cannot reach their potential yield even if nutrients are optimally supplied. Pests and diseases can slow growth rates and greatly reduce the packout. Yields can be substantially reduced by excessive soil wetness or water deficits, and crop nutrient needs are reduced accordingly. A further complication is that lettuce yields may be sharply reduced by over-supply of some nutrients.

These recommendations consider two distinct scenarios (for transplanted crops):

Scenario 1: Potential head yield of 30 t/ha. This is representative of crops growing for 40–60 days in spring, summer or early autumn, producing 60 t/ha of shoot biomass (about 4 t/ha dry matter), planted at 40,000–55,000 plants/ha.

Scenario 2: Potential head yield of 18 t/ha. This is typical of winter crops grown for up to 120 days, producing 36 t/ha of shoot biomass (about 2.4 t/ha dry), at a plant population of 40,000–55,000 plants/ha. Packout on these winter crops may be quite low unless grading standards vary seasonally.

For each scenario the recommendations consider an additional variation where the field yield is 90% of potential. A 10% yield reduction can be expected if the soil is wetter than field capacity for a total of more than 10 days (for a summer crop) or 25 days (for a winter crop). A 10% yield reduction from potential is also what can be expected if the soil pH is 6.5 compared with 5.8 (and the reduction is about 20% if pH is 6.9).

7.2. Nutrients to grow the crop

The recommendations for N, P, K and Mg are based on a reanalysis of work carried out in New Zealand from 2000 to 2003 (Reid et al. 2002a; Searle & Reid 2004). The cultivars examined were 'Casino', 'Target', 'Wintergreen' and 'Victory' grown in Poverty Bay and the Horowhenua. The experiments covered a wide range of combinations of fertiliser rates, potential yields, and planting densities, but conventional analysis of variance could not discern responses to N, K and Mg fertilisers. Pooled results from one site in Poverty Bay, and three sites in the Horowhenua were suitable for fitting the PARJIB model for yield response to nutrient supply (Reid 2002; Reid et al. 2002c). The model accounts for variations in nutrient supply from both the soil and fertilisers. It also accounts for the effects of excessive water on the crop. The model described the field data well, and effects on yield could be quantified for supply of N and P. It could not identify yield responses to K and Mg which appeared to be amply supplied at the experimental sites. There is a risk that the model based on these results underestimated crop N requirements because of considerable nitrate leaching during the experiments. However, it is worth noting that the responses modelled are generally 40–50 kg N/ha less than those calculated from published "optimum" concentrations of N in lettuce crops in the UK (Greenwood et al. 1980b). In turn, the recommendations based on "optimum" values are about 40 kg N/ha less than those based on critical N concentrations.

Here, the N recommendations are based on critical plant N concentrations required for the target yields (Greenwood et al. 1980a). The recommendations assume no leaching of nitrate below the root zone and the majority of the N available from the soil is in the top 15 cm depth, as estimated by the Available N (AMN) procedure. There are likely errors introduced by both assumptions, but they will tend to compensate for each other.

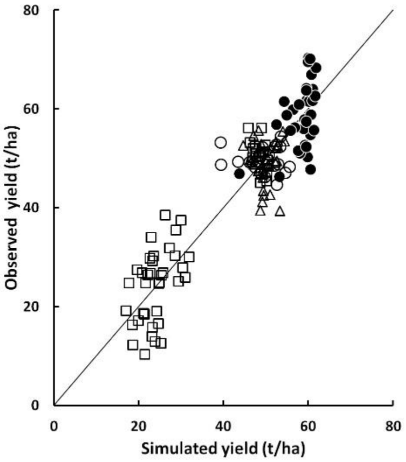


Figure 7-1. Performance of the PARJIB model for lettuce. Measured yields are plotted against the simulated values from the model after calibration. The plotted line is the line of perfect agreement. Solid symbols are results from an experiment conducted with summer lettuce in Poverty Bay; hollow symbols are results from three separate experiments on summer, autumn, and winter sown lettuce in the Horowhenua.

Lettuce can take up considerable amounts of N, and rather less P (Figure 7-2). However, a considerable amount of the N may be left behind in residues if the crop is trimmed at point of harvest. This N will be rapidly mineralised and should reduce N fertiliser requirements for crops planted soon after.

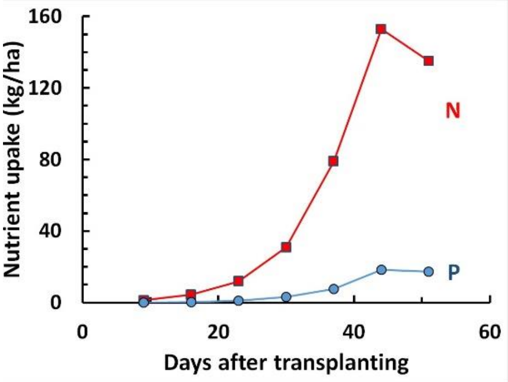


Figure 7-2. N and P uptake by autumn-planted lettuce grown near Pukekohe (Sher 1996b). The crop yielded 56 t/ha fresh and was planted at 66,000 plants/ha (which is high compared with current practice). If the population had been 44,000 plants/ha the total N uptake would probably have peaked at around 90 kg N/ha.

Nutrient recommendations for P here are calculated using the model to achieve 99% of potential yield. Recommendations for K and Mg are based on maintenance calculations because of the lack of response to K and Mg observed in the field experiments.

At high Olsen P values, the PARJIB model used here predicted yield responses that matched well to those measured by Prasad et al. (1988) at Levin. However, at low Olsen P values the model overestimated yields. The reasons for this are unclear but may be connected to variations in pH and soil N status between the plots in the Prasad et al. study. When testing PARJIB against those data we had to assume that soil pH, N, and K supply were always optimal.

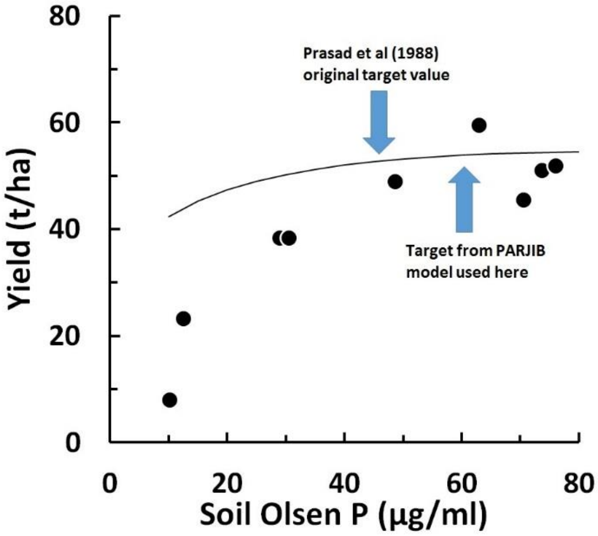


Figure 7-3. Response to soil Olsen P values of lettuce grown at Levin on a soil with a moderately high ASC (c. 76%). The plotted points are from Prasad et al. (1988). The plotted curve is the response simulated using the PARJIB model used for recommendations here. The blue arrows indicate the target Olsen P value recommended by Prasad et al. and a target value derived from the PARJIB model as used here.

Soil tests

Before the crop is planted carry out a soil test from 0–15 cm depth *in each paddock*. If possible sample only the bed areas where lettuce will be grown. Choose the standard soil testing suite (pH, Olsen P, QT Ca, K, Mg and Na, cation exchange capacity and soil volume weight) plus 'Available N' (anaerobically mineralisable N, in kg N/ha).

Key point: Assumed soil bulk densities

The recommendations for lettuce assume the bulk density in the field (ρ_{field}) is 1.1 g/ml and the bulk density of air-dried sieved soil in the laboratory (*volume weight*, ρ_{lab}) is 0.9 g/ml. These values can be used to make the nutrient recommendations below more specific to a site if measured values of ρ_{field} and ρ_{field} are known (see Chapter 2, PARJIB and soil bulk density).

Nitrogen (N)

Most of the nutrient uptake will occur a month or more after transplanting (see Figure 7-2). Measurements of N uptake in New Zealand lettuce crops range from 80 to 150 kg N/ha (Norris et al. 2018; Sher 1996b). However, often it is difficult to demonstrate lettuce yield responses to N fertiliser unless the soil is particularly infertile (Norris et al. 2018; Reid et al. 2002b; Searle & Reid 2004). This difficulty arises partly because lettuce is quite efficient at extracting N from surface layers of the soil, partly because lettuce may take up luxury amounts of N, partly because much of the N taken up remains in the outer leaves that are discarded at harvest, and partly because yields are strongly dependant on grading standards imposed at harvest.

As shown above, little of the N uptake will occur in the 3 weeks or so after transplanting. This heightens the risk of nitrate leaching from starter fertiliser. If wet weather is likely (e.g. for winter-planted crops), large applications of soluble N fertilisers should be avoided in those first 3 weeks.

Here, the N recommendations are based on critical plant N concentrations required for the target yields. The recommendations assume no leaching of nitrate below the root zone and the majority of the N available from the soil is in the top 15 cm depth, as estimated by the Available N (AMN) procedure. There are probable errors introduced by both assumptions, but they will tend to compensate for each other.

The total N fertiliser recommendations are given in the table below.

	Recommended N application (kg N/ha) to grow the crop			
	Scenario 1: Potential head yield of 30 t/ha		**Scenario 2: Potential head yield of 18 t/ha**	
Soil Available N (kg N/ha)	Field yield same as potential	Field yield 90% of potential	Field yield same as potential	Field yield 90% of potential
20	120	120	65	65
40	100	100	45	45
60	80	80	25	25
80	60	60	5	5
100	40	40	nil	nil
120	20	20		
140	nil	nil		

At planting:

- Soluble and controlled release N fertilisers are best incorporated or knifed in 2–5 cm from the plant row. They may be spread as a band on the soil surface provided that irrigation or rainfall is imminent.
- **If using only soluble N fertilisers** like urea, ammonium sulfate, or CAN then apply no more than 20 kg N/ha, or up to 50 kg N/ha if this is a winter-planted crop and wet weather will greatly limit opportunities for side-dressing in the second and third months of growth.
- **If using controlled release N fertilisers** then apply up to 100 kg N/ha of N recommendation as controlled release product and up to 20 kg N/ha of it as a soluble N fertiliser. Ensure the controlled-release formulation will release its N within the expected duration of the crop.

Apply the remainder of the recommended N in one or more side-dressings after the first month of growth. Avoid applying more than 50 kg N/ha at any one time. Side-dressings may be spread on the soil surface (if possible just before light rain or irrigation) or lightly incorporated; use readily available forms of N like urea. Be careful to avoid fertiliser lodging amongst the leaves where it can cause cosmetic damage.

If applying N in the form of composts, incorporate these at least 2 weeks before planting.

If fertigation is available, split the recommended N fertiliser across several applications during growth. This can greatly assist in matching N fertiliser supply with the demands of the crop, but wet weather may restrict the opportunities to fertigate. Yields may be reduced more by excessive soil wetness than by missing one or two small applications of N.

Nitrogen and lettuce quality

Excessive use of N fertilisers may encourage growth of the wrapper leaves, slowing plant trimming at harvest. It may also increase the risk of tip-burn (localised Ca deficiency in the heart leaves) but there is no strong experimental evidence for this under New Zealand conditions.

Phosphorus (P)

Lettuce appears to yield best at moderately high soil Olsen P values (Prasad et al. 1988), and on fresh land with low Olsen P, fertiliser P applications may need to be quite large for the first lettuce crop in a sequence. However, lettuce removes only small amounts of P from the land, and large dressings for the first crop will greatly reduce the fertiliser requirements of the following crops. *It is important to get fresh soil tests carried out before each crop*.

There is a history of excessive P fertiliser use on some lettuce growing land, which shows as soil Olsen P values that are well above the accepted optimum ranges for lettuce (Reid et al. 2002a; Searle & Reid 2004). This is an environmental concern, but there is an economic downside too: *lettuce growth rates and yields can be reduced by excessive P* (Reid et al. 2002a), making the money spent on the extra fertiliser doubly wasted.

Stresses due to, say, excessive soil pH or waterlogging greatly reduce the responsiveness of the crop to P fertiliser.

If using composts or slowly soluble P fertilisers, broadcast and incorporate these before planting.

If using soluble P fertilisers, apply as much as possible of the recommendation in bands. If P fertiliser is required, apply up to 5 kg P/ha as a starter close to the transplant line. If possible, apply about 50 kg P/ha of the remaining recommendation as a band 5–10 cm from the transplant line. The remainder (if any) of the recommendation can be applied pre-planting as a base dressing. *Do not side-dress growing crops with P fertiliser.*

	Recommended P application (kg P/ha) to grow the crop			
	Scenario 1: Potential head yield of 30 t/ha		**Scenario 2: Potential head yield of 18 t/ha**	
Soil Olsen P (µg/mL)	Field yield same as potential	Field yield 90% of potential	Field yield same as potential	Field yield 90% of potential
10	175	130	120	65
20	160	95	80	30
30	140	60	45	nil
40	110	20	5	
50	70	nil	nil	
60	30			
70	nil			

Phosphorus and lettuce quality

There is no clear evidence that P supply noticeable affects lettuce head quality of crops in New Zealand.

Potassium (K)

Experiments in New Zealand have failed to observe lettuce yield or quality responses to K supply. It appears that the soils used for lettuce growing have adequate K available, and the crop is not especially sensitive to K supply beyond the optimum range. If maintenance applications of K are being made then broadcast and incorporate these before or after the crop; either KCl or K_2SO_4 is a suitable choice if applied in this way.

Magnesium (Mg)

Experiments on lettuce in New Zealand have failed to observe any response in yield or quality to Mg fertilisers or soil QT Mg. Maintenance requirements are small (Table 7-1) and it seems most horticultural soils already contain an overwhelming excess of Mg. It will be a sensible precaution to apply a foliar spray of Mg at manufacturer's recommended rates *if there have been clear visual symptoms of Mg deficiency in previous lettuce crops at the same site*. The symptoms are that the older leaves turn yellow beginning at the edges, but the veins often remain green. Some marbling may be seen.

Calcium (Ca) and lime

Localised Ca deficiency is associated with tip-burn in lettuce. Soil applications of Ca fertilisers are very unlikely to affect this because the soil already contains a large amount of Ca, and tip-burn is usually caused by competition between wrapper and heart leaves for water (which transports Ca with it). Foliar Ca sprays (at manufacturer's recommended rates) may be of some benefit if they penetrate to tip-burn-susceptible regions, but this will vary between lettuce head types and cultivars.

Previous recommendations (Wood et al. 1986) were that soil pH should be kept in the range 6.0–7.0. However, it is difficult to find an experimental basis for this, and reanalysis of the experiments used to fit the PARJIB model (Reid et al. 2002a; Searle & Reid 2004) now suggest that pH values >6 can decrease yield, and at pH 7.0 yields may be depressed by about 20%. Further research is needed, because many growers have maintained soil pH between 6 and 7, following the earlier recommendations. On the basis of the experimental evidence available:

- Apply lime only if pH is less than 5.5, targeting a pH of 6.0
- Apply fine lime at least a month before planting.

Sodium (Na)

Do not apply Na fertilisers to lettuce in New Zealand. Small amounts of Na present in some compound fertilisers are unlikely to be harmful.

Sulfur (S)

Yield or quality responses to fertiliser applications of S have not been documented in New Zealand. Soils used for lettuce in New Zealand usually contain adequate quantities of S already because S is commonly applied as part of other fertiliser applications (such as superphosphate or SOP).

Trace elements

Applications of trace elements to New Zealand lettuce crops are unlikely to generate an economic return, unless there is strong evidence that specific deficiencies have occurred on previous crops at that site. An exception might be if foliar testing confirms a trace element deficiency. In that case a foliar spray (at manufacturer's recommended rates) is probably best. Maintenance applications are of the order of a few g/ha and availability of these nutrients is so dependent upon pH and changes in soil aeration (water content) that trace elements applied to the soil can be ineffective.

7.3. Maintenance nutrient applications

Maintenance applications of any particular nutrient should be made only if none will be applied to grow the crop. For N, maintenance applications should be considered only under organic production systems using composts.

Table 7-1. Uptake of major nutrients removed from the soil by a lettuce crop with a shoot biomass yield of 56 t/ha (3.7 t DM/ha). This corresponds to a marketable yield of about 28 t/ha. The values were measured on a crop grown near Pukekohe in 1994 (Sher 1996b).

	N	P	K*	S	Ca	Mg
Total uptake into the shoot biomass (kg/ha)	135	17	312 (135)	9	45	10

*The plant K concentrations reported by Sher seem unusually large; they are much larger than the critical K concentrations cited below, yet the N concentrations are similar to the critical N concentrations. Furthermore, plant N and K concentrations are usually similar (Greenwood & Stone 1998). The values in parentheses were calculated assuming that K uptake was the same as N uptake.

Maintenance requirements should be calculated from the kg of each element *per tonne of heads removed from the field*. Often reject heads and trimmings are returned to the field at harvest, so the nutrients in those are recycled. If 30 t/ha of heads are removed from the field the maintenance P applications need to be 30 x 0.31 = 9.3 kg P/ha.

Table 7-2. Typical amounts of major nutrients removed from the soil by lettuce crops. These values assume the crop is trimmed in the field. These values are based on the results in Table 7-1.

	N	P	K	S	Ca	Mg
kg/t shoot removed from field	2.4	0.31	2.4	0.17	0.81	0.18
Offtakes (kg nutrient/ha)						
Marketable yield 30 t/ha	73	9	73	5	24	5
Marketable yield 18 t/ha	44	6	44	3	15	3

Nutrient concentrations can vary between crops and the figures above may reflect luxury uptake of some nutrients, and so regularly applying the amounts calculated from those figures may unnecessarily inflate soil test values. It is a good idea to keep track of trends in soil test values over several years to ensure that they do not become excessive.

For methods of application of P follow the guidelines for nutrients to grow the crop.

If Olsen P>70, do not apply any maintenance P (allow Olsen P to decrease).

If QT K>10, do not apply maintenance K. If maintenance applications of K are being made then broadcast and incorporate these at least 2 weeks before planting. Either MOP or SOP is a suitable choice if applied in this way.

7.4. Plant analysis

Laboratories may quote typical nutrient concentrations in leaves of lettuce using results collated from crops in New Zealand. Comparisons with critical or optimum nutrient concentrations is a better guide to whether a crop is experiencing a nutrient deficiency. Even so, plant nutrient analysis is of limited use for lettuce management decisions in-season:

- Critical and optimum concentrations vary with plant size
- The time taken to sample, measure, and then interpret nutrient concentration data can be considerable, and the crop is usually of short duration
- The most reliable information for critical or optimum concentrations is for plants at harvestable maturity.

However, plant nutrient analysis can be helpful in planning fertiliser regimes for the following crops at the same site. Sample whole plants (above ground) at harvest and compare nutrient concentrations with the values tabulated below. It is also useful to measure the fresh and dry masses of the plants after drying at 70°C, and compare these with the values in the table, because the optimum and critical concentrations of N, K, and maybe P, decrease as the plants grow larger.

Critical concentrations of N, P and K for lettuce can be interpolated from Figure 1 of Greenwood et al. (1980a) and these are given in Table 7-3. However, “Optimum” N, P and K concentrations have also been published (Greenwood et al. 1980b, c, d) and these seem to be substantially less. The reasons for this disparity are unknown, but deserve further investigation under New Zealand conditions.

Table 7-3. Critical concentrations of N, P, and K in lettuce (Greenwood et al. 1980a). Values are given on a dry mass basis for the whole shoot, assuming the % dry matter (% DM) is 6.7%.

Dry mass (g/plant)	Fresh mass (g/plant)	Critical nutrient content (% DM)		
		N%	P%	K%
0.3	4	6.1	0.73	6.0
4.4	66	5.0	0.66	5.2
23	334	3.4	0.49	4.2

Table 7-4. Optimum nutrient concentrations for lettuce (Greenwood et al. 1980b, c, d). Values are given on a dry mass basis for whole plants (above-ground) at harvestable maturity weighing about 18 g dry (235 g fresh).

	Nutrient concentration (%)
Nitrogen (N)	2.42
Phosphorus (P)	0.35
Potassium (K)	2.12

Most likely deficiency symptoms

See Table 7-5. Excellent images of these symptoms were published by Scaife and Turner (1983). Helpful images are also available from the Yara CheckIT app for mobile telephones (Yara 2017), although the accompanying descriptions are sometimes at odds with New Zealand experience of where such deficiencies may occur. Wood et al. (1986) also outline many of the possible deficiency symptoms.

Table 7-5. Possible nutrient deficiency symptoms of lettuce grown in the field under New Zealand conditions. The descriptions of symptoms are adapted from those of Scaife and Turner (1983) and Wood et al. (1986).

Nutrient	Symptoms	Notes
N, nitrogen	Wrapper leaves pale green/yellow	
P, phosphorus	Slowed growth, failure to heart.	
K, potassium	Old leaves scorch and deform, failure to heart.	Rarely seen under New Zealand conditions.
S, sulfur	New leaves uniform yellow colour.	Rarely seen in New Zealand crops, perhaps because many commonly used P and K fertilisers contain S also.
Ca, calcium	Brown or grey lesions on young leaves in particular (“tip-burn”).	Some tip-burn of young leaves may occur under dry conditions even though rest of plant has ample Ca.
Mg, magnesium	Older leaves yellow beginning at edges, but the veins often remain green. Some marbling may be seen.	Sometimes confused with virus infections. No verified cases of Mg deficiency in lettuce crops reported in New Zealand.
Cu, copper	Leaves are especially long and cupped. Plants stunted and fail to heart.	May be associated with high soil pH, but most serious on peats regardless of soil pH.
B, boron	Similar to Ca deficiency, but growing point may be quite blackened.	
Zn, zinc	Papery dead areas with dark margins between veins on older leaves.	Most likely associated with high soil pH or organic soils.

8 Onions

Bulb onions are mostly grown around Pukekohe, Northern Waikato, Hawke’s Bay and Canterbury. Nutrient supply must be managed carefully because the crop has an unusual root system.

The root system is shallow. This makes it poor at extracting N from below about 25 cm soil depth – heavy rainfall or irrigation may leach fertiliser N beyond reach of the roots. Mineral N released from soil organic matter will be leached also, *but it is subsequently replaced by microbial action in the topsoil*. To lessen the risks of nitrate pollution, for onions give preference to sites that have a high potential to mineralise N from soil organic matter, so they need less N fertiliser. Planting a deep rooting crop after onions also reduces potential nitrate leaching.

The root system is poorly branched with few or no root hairs. This makes it poor at extracting phosphate (P) from soil. This has led to a history of large P fertiliser applications for onions. Repeated growing of onions runs the risk of raising soil P concentration to the point where it is an environmental risk. This can be avoided by soil testing before each crop and smarter placement of whatever P fertiliser the crop actually needs.

The optimum soil test ranges for nutrients – and the likelihood of fertiliser applications being profitable – depends strongly on potential yield. In turn this is influenced by sowing date and weather (the timing of bulbing is influenced by changes in day length), variety, and plant population density. For nutrient management we need to consider potential yields on the basis of the dry not fresh mass of bulbs, because cultivars may differ greatly in bulb dry matter percentage.

8.1. Potential, field, and marketable yields

The nutrient requirements of onions depend strongly on potential yield. In turn, this is influenced by sowing date and weather, variety, and plant population density. *We must consider potential yields of the basis of the dry mass of bulbs, because varieties may differ greatly in bulb dry matter % (DM%).*

Here we outline nutrient recommendations for two broad situations:

Scenario 1: Potential yield is 10.0 t/ha of bulb dry matter. This is typical of long-keeper crops grown for storage and export where fresh marketable yields are about 60–80 t/ha at 10–13% bulb DM%.

Scenario 2: Potential yield is 6.0 t/ha of bulb dry matter. This is typical for sweet, red, and white onions and early crops not grown for storage. These crops have potential yields of about 100 t/ha fresh and marketable yields are often 50–80 t/ha, but their bulb DM% values are about 6%. This scenario can be representative also of late-planted long-keeper cultivars with lower fresh yields but higher DM%.

Potential yields of long keeper cultivars grown around Pukekohe are often close to those of scenario 1, but field yields may be less (6–10 t/ha of bulb dry matter) because of pressures from plant diseases. In those cases, maintenance nutrient applications should be adjusted to reflect the smaller amounts of material removed from the field.

8.2. Nutrients to grow the crop

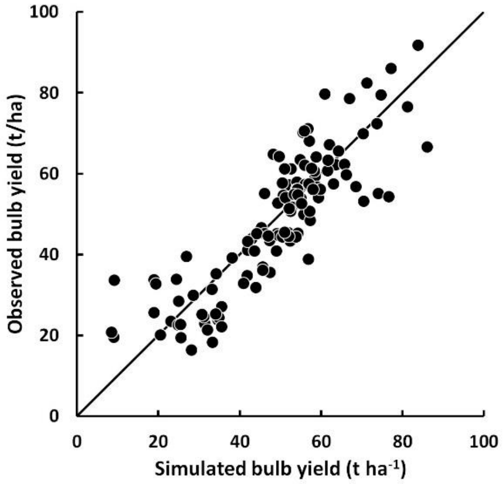


Figure 8-1. Performance of the PARJIB model for onions. Measured bulb yields are plotted against the simulated values from the model after calibration. The plotted line is the line of perfect agreement. The bulb dry matter yields varied from 1 to 10 t/ha.

The recommendations for N, P, K and Mg are based on three experiments carried out in Hawke's Bay and Canterbury from 1993 to 1996. The experiments covered the cultivars 'Pukekohe Longkeeper', 'Kojak', and 'Encore', with a wide variety of fertiliser types and rates, and with potential yield varying from 6.5 to 8.9 t/ha of bulb dry matter. Bulb dry matter % varied from 4.4 to 14.5%. The soils covered a wide range of availability of N, P and K, but the Anion Storage Capacity (P retention) at all sites was <30%.

The results were collated and analysed by fitting the PARJIB model (Reid 2002; Reid et al. 2002c). The results match well with earlier P response experiments conducted at Levin (Prasad et al. 1988) even though the Levin experiments were conducted on a soil with ASC of 76%. Nitrogen requirements were calculated using the PARJIB model and then cross-checked against values calculated form the critical plant N concentrations (Greenwood et al. 1980a). The latter method gave slightly higher recommendations, and these have been used here.

Key point: Little uptake until bulbing

Onions have very modest nutrient needs until after bulbing when rapid growth starts (often about 80 days after sowing) (see Figure 1-4).

Soil tests

Before the crop is planted start the process of nutrient management with soil testing from 0–15 cm depth *in each paddock*. Choose the standard soil testing suite (pH, Olsen P, QT Ca, K, Mg and Na, CEC and soil volume weight) PLUS 'Available N' (anaerobically mineralisable N, in kg N/ha) PLUS Anion Storage Capacity (ASC or P retention%). ASC needs to be tested only once – not before every crop.

Key point: Assumed soil bulk densities

The recommendations for onions assume the bulk density in the field (ρ_{field}) is 1.1 g/ml and the bulk density of air-dried sieved soil in the laboratory (*volume weight*, ρ_{lab}) is 0.81 g/ml. These values can be used to make the nutrient recommendations below more specific to a site if measured values of ρ_{field} and ρ_{field} are known (see Chapter 2, PARJIB and soil bulk density).

Responses to fertilisers will be strongly reduced if the crop suffers water stress. We have assumed there is no water stress or pressure from pests and diseases.

Nitrogen (N)

If fertigation is available, use this to split recommended N applications through the season.

Onions have very modest N needs until after bulbing when rapid growth starts (often about 80 days after sowing) (see Figure 1-4).

Key point: Split N applications

In wet areas, or if irrigation is frequent, split applications of soluble N. Aim for two or more small applications spread through the season.

If using solid fertilisers, apply up to 20 kg N/ha of soluble or 40 kg N/ha of controlled-release fertiliser as a starter down the spout or banded close to the plants. Broadcast the remainder of the recommended N in at least two side-dressings of soluble N fertiliser once the rapid growth phase starts. Exceptions are composts that are best incorporated at least 2 weeks before sowing.

Available N (kg N/ha)	Recommended N application (kg N/ha) to grow the crop	
	Scenario 1: Potential yield 10 t/ha bulb dry matter	Scenario 2: Potential yield 6 t/ha bulb dry matter
20	140	80
40	120	60
60	100	40
80	80	20
100	60	nil
120	40	
140	20	
160	nil	

Nitrogen and onion quality

Early New Zealand experience suggested little effect of N fertilisation on storage properties of 'Pukekohe Longkeeper' (Ceesay 1980). However, there is now evidence that N fertilisers can affect onion quality, especially if more is applied than required to achieve the potential yield. Overseas, Díaz-Pérez et al. (2003) and Tekalign et al. (2012) found that applying N fertilisers may increase bulb pungency while reducing storage life. In New Zealand Wright (1993) found that compared to applying 120 kg N/ha, 240 kg N/ha increased the incidence of bulb rots during storage. He also reported that storage rots were stimulated by late applications of N. Searle (personal communication 2018) has found that bulb pungency may be increased by application of N fertilisers. Excessive N supply may increase the incidence of thick necks in bulb onions (Syed et al. 2000), and bolting in bunching onions (although firm evidence for this in bulbing onions is hard to find). Inadequate N supply may also increase bolting in bulb onions (Díaz-Pérez et al. 2003).

Phosphorus (P)

High ASC values lower the efficiency of P fertilisers – so band soluble P fertiliser as much as possible. This reduces the percentage that is fixed onto soil surfaces. *There is no evidence that high ASC values increase the optimum or target Olsen P for vegetables.*

If using slowly soluble organic or mineral P fertilisers, then these can be bulky and pose some risks if concentrated close to the seeds. Broadcast most of the recommendation before planting, but retain a portion to band 5–10 cm from the drill line at planting. **If using soluble P fertilisers** then apply as much as possible of the recommendation in bands, especially if soil Olsen P is low. If P fertiliser is required, apply up to 10 kg P/ha as a starter down the spout or banded close to the drill line – but avoid scorching germinating seeds. If possible, apply about 50 kg P/ha of the remaining recommendation as a band 5–10 cm from the drill line. The remainder (if any) of the recommendation can be broadcast pre-planting. Side-dressed P is very unlikely to be taken up by the crop.

If using composts, broadcast and incorporate these before planting.

If using soluble P fertilisers, apply as much as possible of the recommendation in bands, especially if soil Olsen P is low. If P fertiliser is required, apply up to 10 kg P/ha as a starter down the spout or banded close to the drill line – but avoid scorching germinating seeds. If possible, apply about 50 kg P/ha of the remaining recommendation as a band 5–10 cm from the drill line. The remainder (if any) of the recommendation can be applied pre-planting as a base dressing. Side-dressed P is very unlikely to be taken up by the crop.

Soil Olsen P (µg/mL)	Recommended P application (kg P/ha) to grow the crop	
	Scenario 2: Potential yield 10 t/ha bulb dry matter	Scenario 1: Potential yield 6 t/ha bulb dry matter
10	up to 270	up to 140
20	200	70
25	170	40
30	140	15
35	100	nil
40	70	
45	30	
50	20	
>55	nil	

A note on target Olsen P values

The 1986 Fertiliser Recommendations gave target Olsen P values that now seem too high. Figure 8-2 shows the response curve used here (from our analysis of crops in Hawke's Bay and Canterbury on soils with ASC<30%). It also plots the original data used for the 1986 recommendations (from crops at Levin on a soil with ASC of 76%). The original data agree well with the model used here.

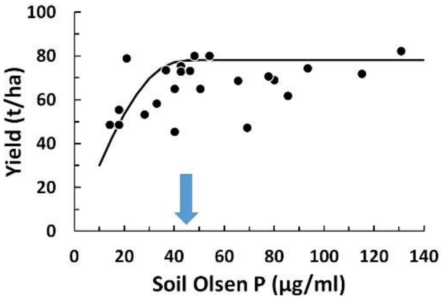


Figure 8-2. Onion yield response to Olsen P as measured by Prasad et al. (1988). The arrow indicates the target Olsen P proposed by Prasad et al. The 1986 recommendations used the same data but proposed a target about 75 µg/mL for the same soil. The solid black line is the predicted response from the model used here, with a potential yield of 8.4 t/ha of bulb dry matter.

Potassium (K)

Do not apply K fertiliser to grow the crop, but a maintenance application may be required (see below).

New Zealand soils are often rich in K. Experiments in New Zealand generally fail to find onion yield responses to K fertiliser. Although details were not presented, Wilson and Scheffer (1983) found no responses of onions to K fertiliser at QT K values down to 8. Our modelling analysis of the available data suggests positive yield responses may occur when potential yield is large and QT K is <4 (a rare set of circumstances). Even so, the yield response is very gradual and K fertiliser application will rarely be profitable. Furthermore, the same analysis suggests K fertiliser may *decrease* yield if potential yield is small and QT K is >10.

Magnesium (Mg)

It appears there are no verified cases of Mg deficiency or yield response to Mg fertiliser in New Zealand onion crops. It seems most horticultural soils in New Zealand already contain an excess of Mg. It will be a sensible precaution to apply a foliar spray of Mg at manufacturer's recommended rates *if there have been clear visual symptoms of Mg deficiency in previous onion crops at the same site*. The symptoms are mainly that the older leaves turn yellow along their entire length without dying back.

Calcium (Ca) and sodium (Na)

Soils used for vegetables in New Zealand usually contain large quantities of Ca already.

It is very unlikely that onion yields will respond to applications of Ca. There has been a suggestion that Ca applications may improve bulb skin quality, but firm evidence of this remains elusive.

Do not apply Na to onion crops in New Zealand.

Lime requirements

The optimum pH appears to be 6.05 and yield appears to fall away sharply between there and pH 5.5. Our modelling indicates dry matter yields decrease by about 30% between pH 6 and pH 5.5. Experiments at lower pH values have not been reported. Soil pH values above 6.5 may cause trace element deficiencies and should be avoided.

- Apply lime only if pH is less than 5.9, targeting a pH of 6.2.
- If applying close to sowing, use fine lime. Generally apply lime as early as possible before planting.

Sulfur (S)

Soils used for vegetables in New Zealand usually contain adequate quantities of S already and S is commonly applied in other fertilisers such as superphosphate and SOP. You are very unlikely to get a yield response to S applied in fertiliser although often onions will take up much more S than they need for maximum yield ("luxury uptake"). Luxury concentrations in the bulbs increase onion pungency (McCallum et al. 2005; Randle et al. 2002) and may increase storage life.

You will need to decide whether to apply maintenance S on the basis of the quality characteristics you want for this and future crops grown at the site. Depleting soil S may be advisable if you wish to grow sweet onions. Applying S containing fertilisers may be beneficial if previous onion crops grown at this site have suffered significant problems with storage life.

Trace elements

Applications of trace elements to New Zealand onion crops are very unlikely to be economic, unless there is strong evidence from previous crops that specific deficiencies have occurred. Maintenance applications are very small and availability of these nutrients is so dependent upon pH and soil water content that trace element applications to the soil will usually be wasted. Potential exceptions could be B on sedimentary soils following a wet winter and spring, and Cu on organic soils. In those cases the best option may be foliar sprays at the manufacturer's recommended rates. These are best applied in the early morning or evening to extend the drying time and opportunity for the nutrient to enter the leaves.

8.3. Maintenance nutrient applications

Maintenance applications of any particular nutrient should be made only if none will be applied to grow the crop. For N, maintenance applications should be considered only under organic production systems using composts. Depleting soil S (by not applying S containing fertilisers) may be advisable if future crops will include sweet onions.

Table 8-1 shows the approximate amounts of nutrients that can be taken up by onion crops in New Zealand. The values in the tables are typical – nutrient concentrations can vary between crops. Also, the values probably reflect a considerable amount of luxury uptake of some nutrients – the uptake required to achieve potential yields is likely to be rather less. This is particularly true for Ca and S.

Table 8-1. Amounts of major nutrients taken up from the soil by a 59 t/ha onion crop of 'Pukekohe Longkeeper' grown at Pukekohe that yielded 59 t/ha fresh, 7.5 t/ha dry (data calculated from Sher (1996a)).

	N	P	K	S	Ca	Mg
Total uptake (kg/ha)	218	32	204	54	108	13

*Table 8-2. Typical offtakes of major nutrients removed from the soil by bulb onion crops. These are calculated from Table 8-1 on the basis of the **dry** mass of bulbs removed from the field.*

	N	P	K	S	Ca	Mg
kg/t bulbs dry	15.0	2.2	14.0	3.7	7.4	0.9
Offtakes (kg/ha)						
Removed yield 8 t/ha dry	120	18	112	30	59	7
Removed yield 5 t/ha dry	75	11	70	18	37	4

Maintenance applications are best calculated on the basis of dry matter yields removed from the paddock and nutrient contents. Multiply the target dry bulb yield in t/ha by the kg of each element taken up or removed per tonne of *dry* bulbs removed from the field (Table 8-2).

These are best calculated on the basis of dry matter yields removed from the paddock and nutrient contents. Multiply the target dry bulb yield in t/ha by the kg of each element taken up or removed per tonne of *dry* bulbs removed from the field (see Table 8-2). For a crop where 8 t/ha of dry bulbs are removed from the field the offtake of P would be about 8 x 2.2 = 18 kg P/ha.

Generally, fertiliser K for maintenance purposes should be *broadcast and incorporated either before planting or after harvest*. Potassium sulfate (SOP) is normally used. Management aims may include reducing soil S concentrations for long-term control of onion pungency. In that case use MOP for all or part of the K maintenance application, but apply it after harvest to reduce the risks of negative effects of Cl on the crop.

8.4. Plant analysis

Laboratories may quote typical or adequate nutrient concentrations in leaves using results collated from crops in New Zealand. These cannot indicate if the crop is deficient in any nutrient and might respond to fertiliser application. A more useful measure is the *critical nutrient concentration,* below which plant growth is adversely affected (Table 8-3). For onions critical nutrient concentrations have been established only for N, P and K.

Sampling of whole shoots or whole bulbs when they are about 2 cm diameter can be useful for determining if further N fertiliser could improve yield, but it is too late for adjusting P and K supply. For strategic decisions affecting nutrient supply to future crops you can sample whole bulbs at final harvest.

Table 8-3. Critical nutrient concentrations for onions. Concentrations are given on a dry mass basis. [1] from Greenwood et al. (1980a) assuming 10% dry matter content, [2] from Piggot (1986).

Nutrient	Whole plant about 20g fresh mass[1]	Whole plant about 90g fresh mass[1]	Mid-growth, 2 cm bulb[2]	Around harvest, whole bulb[2]
N %	2.5	1.6	2.75	
P %	0.65	0.23	0.3–0.4	0.3
K %	3.3	1.8		1.5

Most likely deficiency symptoms

Excellent images of these were published by Scaife and Turner (1983). Helpful images are also available from the Yara CheckIT app for mobile telephones (Yara 2017), although the accompanying descriptions are sometimes at odds with New Zealand experience of where such deficiencies may occur.

Table 8-4. Nutrient deficiency symptoms of onions under New Zealand conditions. The descriptions of symptoms are adapted from those of Wood et al. (1986).

Nutrient	Symptoms	Notes
N, nitrogen	Stunted and thin growth. The leaves are pale – older leaves turn yellow and die back from the tip.	
P, phosphorus	Poor growth, with dull green leaves, and the older leaves may die back from the tip.	These are also symptoms of a number of other problems, be cautious in diagnosing P deficiency from visual symptoms.
K, potassium	Older leaves die back from the tip without first becoming yellow.	Rarely seen under New Zealand conditions. Symptoms are common to a number of other problems.
S, sulfur	Leaves thick and deformed, new leaves yellow.	Rarely seen in New Zealand crops.
Ca, calcium	Die back of young leaves without prior yellowing.	Extremely unlikely in New Zealand.
Mg, magnesium	Older leaves yellow along entire length without die back.	No verified cases of Mg deficiency in onions in New Zealand.
B, boron	Older leaves chlorotic and die back. Leaves crack transversely.	
Mn, manganese	Striped chlorosis of outer leaves which later die. Growth severely decreased.	
Cu, copper	Tips of young leaves become chlorotic, turn white and twist or spiral. Bulb scales yellow and thin – bulb soft.	May be associated with high soil pH, excessive soil water contents, or over-supply of other trace elements. Bulb symptoms shared by other disorders.
Zn	Leaves striped yellow, twisted and stunted.	Generally associated with high soil pH. Difficult to distinguish from Mn deficiency.

9 Peas for processing

Peas for processing ("vining" or "garden" peas) are now grown mainly in Canterbury, Marlborough, Hawke's Bay and Poverty Bay; they have also been produced in the Manawatu region. Frozen peas are an important export from New Zealand.

Pea yields in New Zealand are extraordinarily variable between and within paddocks and growing seasons, which perhaps raises anxieties among growers whether their crops receive enough mineral nutrients. The reasons for the yield variability are still uncertain, but it seems very unlikely that insufficient nutrient supply is an important factor.

From roughly 1970 through to 2008 in New Zealand at least 25 separate field experiments sought to quantify pea responses to fertiliser (Carter & Stoker 1988; McLeod 1987; PIDG 2008; Wilson et al. 1999); none of these have provided convincing evidence that pea yields respond to N, P, K fertilisers or lime. In one of seven trial conducted in South Canterbury from 1970 to 1978, there was a suggestion that superphosphate increased average seed yield of peas (McLeod 1987), but no formal statistical analysis was carried out so it is unknown whether the difference would have met any accepted criteria for statistical significance. Growers sometimes believe they have seen benefits from starter fertilisers applied to peas. As McLeod (1987) pointed out, crop appearance can be deceptive; fertilisers containing N and Mo in particular can result in "darker, leafier, more bulky crops" but the scientific evidence is that this rarely results in increased pea yields.

9.1. Potential yields

Potential yields are influenced strongly by the choice of variety, weather conditions (and hence planting date), and the required maturity at harvest (Wilson 1987). Crops producing a large biomass do not necessarily yield the greatest pea yields, and the factors controlling harvest index are still under investigation. This makes it hard to specify what the potential yields if growers and scientists can conquer the variability within and between crops. Nutrient recommendations here assume a potential yield of 15 t/ha of peas for processing – certainly some crops do achieve that.

9.2. Nutrient recommendations

The lack of yield responses to fertilisers in New Zealand experiments meant that it was impossible to calibrate and use the models used for other crops in this book. Wood et al. (1986) and Wallace (2000) gave recommendations for fertiliser applications to achieve target soil test values. However, the scientific support for those target values is very weak. Indeed the very lack of yield responses in the field experiments cited above means that target values could only be estimated by assuming they are less than the minimum soil test values achieved in the experiments (see also Figure 2-3). *Here recommendations are based on offtake or maintenance requirements.*

Estimated offtakes (Table 9-1) are based on overseas data.

Table 9-1. Estimated offtakes of N, P and K by a process pea crop with potential yield of 15 t/ha of pods. The values are based on data from USA (USDA 2018).

	N (kg N/ha)	P (kg P/ha)	K (kg K/ha)
kg nutrient/t pods	2.9	0.30	1.8
offtake by a 15 t/ha crop	44	5	27

Estimate maintenance requirements from the kg of each element *per tonne of peas removed from the field* (see Table 9-1). A crop yielding 10 t/ha of peas would remove about 10 x 0.30 = 30 kg P/ha in the peas. Nutrient concentrations can vary between crops, and the values in Table 9-1 may reflect luxury uptake of P and K in particular.

Soil tests

Before the crop is planted, carry out soil testing for each paddock from 0–15 cm depth. Choose the standard soil testing suite (pH, Olsen P, QT Ca, K, Mg and Na, CEC and volume weight).

Nitrogen (N)

Do not apply N fertiliser to process peas.

There is no scientific evidence to support applying N fertiliser to process peas in New Zealand. Wilson et al. (1999) tested soils with Available N concentrations down to 73 kg N/ha and found no response to N fertiliser in peas. Peas are legumes that have the potential to fix much of their own N requirements, but the proportion of plant N that peas fix decreases as the soil mineral N supply increases. Under Canterbury conditions, with soil mineral N levels of about 50 kg N/ha at planting peas fixed only 20% of the total plant N (Haynes et al. 1993). As pointed out by (McLeod 1987), an ample N supply of N from the soil or fertiliser may increase vine growth but not pea yield.

Phosphorus (P)

A maintenance P application for a crop yielding 15 t/ha would be about 5 kg P/ha (Table 9-1). Unless soil Olsen P is <10 ppm pea yield responses to this fertiliser are very unlikely.

Use the most rapidly available form of P that is available and suitable for your growing system. Apply this down the spout at planting. Side-dressing P to growing crops is very unlikely to benefit their yield.

Do not apply maintenance P if soil Olsen P>50.

Potassium (K)

A maintenance K application for a crop yielding 15 t/ha would be about 27 kg K/ha (Table 9-1). Use the cheapest source of readily available K that you have available. Apply K fertilisers by broadcasting and incorporating before planting.

Do not apply maintenance K if QT K>10.

Calcium (Ca) and lime

There is no indication that natural levels of Ca in vegetable growing soils limit pea yield or quality in New Zealand. Lime requirements depend on the soil type and its pH. Previous recommendations were to keep soil pH above 5.1 (Wood et al. 1986), and 6.0 (PIDG 2008), but experimental evidence to date indicates no response to lime at pH 5.4 (McLeod 1987).

Apply lime if pH is less than 5.4, targeting a pH of 6.0; values appreciably above 6.5 may cause trace element deficiencies.

Magnesium (Mg), Sulfur (S), and trace elements

Yield or quality responses to applications of these elements are unlikely in New Zealand, and maintenance requirements are small. In the cases of Mg and S, it is better to apply these nutrients to crops for other crops in the rotation where and when soil tests indicate a response is likely. There is no scientific evidence of pea crops responding to applications of trace elements in New Zealand.

9.3. Plant analysis

Typical concentrations in the foliage or even whole plants are of little use. It is very difficult to establish critical concentrations of nutrient elements in peas grown in the field, and for N, P and K at least these critical concentrations decrease markedly as the plants grow larger (Table 9-2).

Table 9-2. Critical concentrations for whole plants (above ground) of peas grown in the UK (Greenwood et al. 1980a). Values are given on a dry mass basis.

Plant dry mass (g)	N	P	K
0.56	5.6	0.47	3.4
23	3.4	0.40	2.2
31	2.6	0.33	1.6

Most likely deficiency symptoms

Visual symptoms of nutrient deficiency are rare in New Zealand pea crops. Damage from extreme weather, insects, diseases or sprays are much more likely to cause unusual appearance of the shoots.

10 Potatoes

Potatoes (*Solanum tuberosum* L.) are grown throughout the country for the fresh market. Potatoes for processing are grown mainly in Canterbury, Manawatu, Hawke's Bay, the Waikato and South Auckland. They are a crop that yields poorly if exposed to water and nutrient deficiencies. They have a relatively shallow root system (maximum depth is about 75 cm under good conditions), a large demand for N, and a need for frequent irrigation in many regions. All this can lead to a substantial risk of nutrient leaching if excessive fertiliser is applied (Francis et al. 2003). Furthermore, the quality of tubers for processing can vary considerably, and plant nutrition often appears to be connected with this. So careful nutrient management is particularly important for potatoes.

10.1. Potential, field, and marketable yields

These can greatly influence the crop's requirements for mineral nutrients. Potential yields may be as small as 50 t/ha for winter-planted crops. The majority of potatoes are grown through spring and summer, and their potential yields vary from about 80 t/ha for early-harvest crops through to 100 t/ha for main-crop plantings. In Canterbury at least, field yields are often rather less than potential (Reid et al. 2016a), perhaps because of a combination of inappropriate irrigation and disease; the reasons are still under investigation.

Four representative scenarios are presented here:

Scenario 1: Potential yield of 100 t/ha (23 t/ha dry matter). This would be typical for many cultivars where a long season is possible, for example the cultivar 'Agria' grown in the Waikato region, Hawke's Bay, or Canterbury. The marketable yield in this scenario could be as high as 80 t/ha depending on grading standards and harvest conditions.

Scenario 2: Potential yield of 87 t/ha (20 t/ha dry matter). This is typical for the cultivar 'Russet Burbank' grown in Canterbury. The marketable yield here could be as high as 70 t/ha but will be less if irrigation restricts tuber size.

Scenario 3: Potential yield of 76 t/ha (14 t/ha dry matter). This is representative of table cultivars like 'Nadine' grown for early harvest (small to medium size tubers) in locations like Matamata in the Waikato region. The marketable yield in this scenario could be as high as 65 t/ha depending on grading standards and harvest conditions.

Scenario 4: Potential yield of 50 t/ha (9 t/ha dry matter). This is representative of winter-planted crops of table cultivars in areas like Pukekohe. The marketable yield could be as high as 46 t/ha depending on grading standards and harvest conditions.

Nutrient requirements will be reduced if the crop suffers water stress; here, recommendations assume no water stress.

Nutrient requirements to grow the crop are based on the potential yields for each scenario, but maintenance nutrient requirements have to be based on offtakes, which depend on the mass of tubers that are removed from the field. This depends in turn on harvesting machinery and grading standards. *The offtake calculations here assume 80% of the tuber yield is removed from the field.*

10.2. Nutrients to grow the crop

The recommendations for N were derived using the Potato Calculator (Jamieson et al. 2004; Jamieson et al. 2008; Jamieson et al. 2006).

The recommendations for P, K and Mg are based on fitting of the model PARJIB (Reid 2002; Reid et al. 2011; Reid et al. 2016a) for the cultivars 'Russet Burbank', 'Franica', and 'Ilam Hardy' at seven different sites in New Zealand from 1999 to 2004. The experiments covered a wide range of combinations of fertiliser rates, potential yields, and planting densities. The model's predictions for P responses match well with the independent observations of Prasad et al. (1988).

Nutrient requirements will be strongly reduced if the crop suffers water stress; here, recommendations assume no water stress, and fertiliser recommendations are calculated to achieve 99% of potential yield, assuming no water stress.

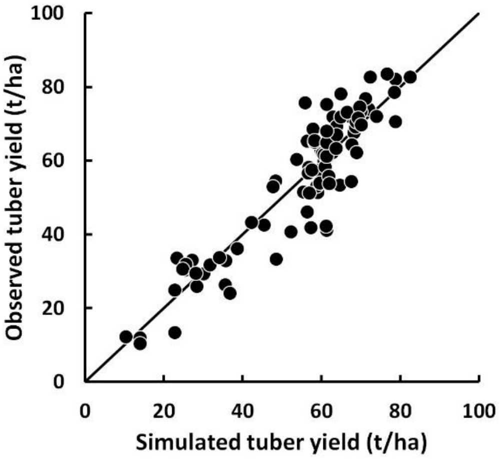


Figure 10-1. Performance of the PARJIB model for potatoes. Measured tuber yields are plotted against the simulated values from the model after calibration. The plotted line is the line of perfect agreement.

Soil tests

Before each crop is planted start the process of nutrient management with soil testing from the paddock at TWO depth ranges:

0–15 cm depth – standard soil testing suite (pH, Ollsen P, QT Ca, K, Mg and Na, CEC and soil volume weight) PLUS Reserve K (TBK, in meq/100g) PLUS Anion Storage Capacity (ASC or P retention%). TBK and ASC need to be tested only once for each paddock – not before every crop.

0–60 cm depth – mineral N test (nitrate plus ammonium, in kg N/ha).

Assumed soil bulk densities

The recommendations for potatoes assume the following values for bulk density in the field (ρ_{field}) and volume weight or bulk density of air-dried sieved soil in the laboratory (ρ_{lab}):

Scenario number	ρ_{field} (g/ml)	ρ_{lab} (g/ml)
1	0.86	0.64
2	1.1	0.81
3	0.86	0.64
4	1.1	0.90

These values can be used to make the nutrient recommendations below more specific to a site if measured values of ρ_{field} and ρ_{field} are known (see Chapter 2, PARJIB and soil bulk density).

Nitrogen (N)

It is important for potatoes to establish ground cover rapidly, and keep green leaves as long as possible. N supply is crucial for this. Recommendations for the total amount of N to be applied are in the following tables.

At planting:

- Soluble and controlled-release N fertilisers are best incorporated or applied down the spout – but make sure they are not in contact with the seed piece. Controlled-release N fertilisers may significantly reduce the risk of nitrate leaching and improve yields in wet weather.
- **If using controlled-release N fertilisers**, apply up to 100 kg N/ha of the controlled-release product and up to 20 kg N/ha of a soluble N fertiliser.
- **If using only soluble N fertilisers** like urea, ammonium sulfate, or CAN, then apply less than half the total recommended N fertiliser (up to 100 kg N/ha if soil N supply is low).

- **Compost sources of N** incorporated at planting may reduce the risk of nitrate leaching, but can be expensive.

Split the remainder of the recommended N across at least one or more side-dressings shortly after canopy closure (or earlier if the crop is struggling to achieve canopy closure). Side-dressings should be readily available forms like urea or CAN.

If fertigation is available, split the recommended N fertiliser across several applications during the season. This can greatly assist in matching N fertiliser supply with the demands of the crop, lessening the risk of nitrate leaching.

Recommendations for N from each scenario reflect the likelihood of N leaching below the root zone as well as the potential yield.

Soil mineral N to 60 cm depth (kg N/ha)	Recommended N application (kg N/ha) to grow the crop	
	Scenario 1: Potential yield 100 t/ha (main crop, table variety)	Scenario 2: Potential yield 87 t/ha (main crop, processing variety)
50	225	225
100	200	175
150	150	125
200	125	100
250	75	50
300	50	nil
350	25	
400	nil	

Soil mineral N to 60 cm depth (kg N/ha)	Recommended N application (kg N/ha) to grow the crop	
	Scenario3: Potential yield 76 t/ha (early harvest, table variety)	Scenario 4: Potential yield 50 t/ha(winter planted crop, table variety)
50	260	230
100	200	195
150	150	188
200	100	182
250	50	175
300	25	140
350	nil	130

*See Key point "Winter rainfall"

Nitrogen and tuber quality

Experiments conducted at Lincoln suggest that excessive N concentrations in the tubers will decrease tuber DM% and specific gravity. Provided N applications are kept within the recommended ranges given above, then detrimental effects on tuber quality are unlikely in commercial crops.

Key point: Winter rainfall

Under Scenario 4 there is considerable potential for nitrate leaching due to winter rainfall in the Pukekohe area. If controlled-release sources of N are used rather than readily soluble N, then the amounts of N recommended are considerably smaller, ranging from 130 kg N/ha (when the soil mineral N is 50 kg N/ha) down to 90 kg N/ha (when the soil mineral N concentration is 350 kg N/ha).

Phosphorus (P)

Potatoes often respond strongly to P fertiliser – *but yield may be suppressed if P supply is beyond the optimum*. If P fertiliser is required, apply up to 15 kg P/ha as a starter down the spout (keeping some separation from the seed piece) or knifed in close to the planting line. If possible, apply up to 50 kg P/ha of the remaining recommendation as a band 5–10 cm from the planting line. The remainder (if any) of the recommendation can be broadcast and incorporated pre-planting. *Side-dressings of P are unlikely to be taken up by the crop.* Do not leave P fertilisers on the soil surface where they will not be effective.

Soil Olsen P (µg/mL)	Recommended P application (kg P/ha) to grow the crop	
	Scenario 1: Potential yield 100 t/ha (main crop, table variety)	Scenario 2: Potential yield 87 t/ha (main crop, processing variety)
10	up to 340	up to 310
20	280	220
30	180	130
35	140	90
40	90	56
45	50	nil
50	nil	nil

Soil Olsen P (µg/mL)	Recommended P application (kg P/ha) to grow the crop	
	Scenario3: Potential yield 76 t/ha (early harvest, table variety)	Scenario 4: Potential yield 50 t/ha(winter planted crop, table variety)
10	up to 200	up to 110
20	110	20
25	60	20
30	30	nil
35	nil	nil

Phosphorus and tuber quality

P nutrition may play an important role in the initiation and setting of tubers. In New Zealand, Reid et al. (2011) found that increasing P supply can increase the number of set tubers and shift the final size distribution towards smaller diameters. This concurs with overseas observations (Allison et al. 2001a; Jenkins & Ali 2000). There is a possible complication here with N supply also, and until such effects are reported more widely, there is insufficient evidence to recommend using fertilisers for manipulation of tuber numbers and sizes.

Potassium (K)

Potatoes can take up large amounts of K, but generally our experiments found only slight responses to K fertiliser in sedimentary soils unless soil QT K was low. This concurs with the results of 33 experiments conducted on sedimentary soils in the UK and a reanalysis of the previous literature by Allison et al. (2001b). Wood (1997) cited results for potatoes grown at Pukekohe that show no consistent relationship between yield and QT K.

The likely response to K fertiliser depends strongly on the mineralogy of the soil. An effective way of dealing with this is to include the Reserve K or TBK value in soil tests. Here we give recommendations for TBK values, of 1, 2, and 3 meq/100g, which covers a wide range of soils used for growing potatoes in New Zealand.

Key point: Applying K fertiliser

K fertiliser is best applied as a base-dressing especially if QT K values are low. *For maintenance applications use the cheapest source of K available (usually MOP) – but it must be broadcast and incorporated at least 2 weeks before planting so that it has chance to equilibrate with the soil.*

Side-dressing will be much less effective.

Scenario 1: Potential yield 100 t/ha (main crop, table variety).

Soil QT K	Recommended K application (kg K/ha) to grow the crop		
	TBK = 1 meq/100g	TBK = 2 meq/100g	TBK = 3 meq/100g
4	340	290	210
5	320	270	150
6	310	240	nil
7	290	200	
8	270	140	
9	240	nil	
10	190		
11	130		
12	nil		

Scenario 2: Potential yield 87 t/ha (main crop, processing variety).

Soil QT K	Recommended K application (kg K/ha) to grow the crop		
	TBK = 1 meq/100g	TBK = 2 meq/100g	TBK = 3 meq/100g
3	330	250	nil
4	320	210	
5	300	150	
6	270	nil	
7	240		
8	190		
9	130		
10	nil		

Scenario3: Potential yield 76 t/ha (early harvest, table variety).

Soil QT K	Recommended K application (kg K/ha) to grow the crop		
	TBK = 1 meq/100 g	TBK = 2 meq/100 g	TBK = 3 meq/100 g
3	320	200	160
4	300	160	nil
5	250	nil	
6	190		
7	160		
8	nil		

Scenario 4: Potential yield 50 t/ha (winter planted crop, table variety).

Soil QT K	Recommended K application (kg K/ha) to grow the crop		
	TBK = 1 meq/100 g	TBK = 2 meq/100 g	TBK = 3 meq/100 g
3	100	100	100
4	nil	nil	nil

Potassium fertilisers and tuber quality

Many have suggested that the form of K fertiliser used can markedly affect tuber quality. The usual suggestion is that use of MOP rather than SOP will reduce tuber dry matter % or specific gravity (Craighead & Martin 2003; Horneck & Rosen 2008). A careful examination of previous experiments led Allison et al. (2001b) to the conclusion that such effects occurred only when the quantity of K fertilisers applied was in excess of the amounts required to achieve maximum yield.

Our results in New Zealand support Allison et al.'s conclusion. If the quantities of K applied do not exceed the recommendations for yield given above, and if the K is applied as a base dressing, it is very unlikely that there will be a decline in tuber quality associated with use of MOP rather than the more expensive SOP.

Magnesium (Mg)

There appears to be no verified case of Mg deficiency or yield response to Mg fertiliser in New Zealand potato crops. There is anecdotal evidence that low Mg concentrations are sometimes obtained in petiole testing. The calibration of potato petiole test results against fertiliser response in New Zealand is poorly documented. It seems most horticultural soils in New Zealand already contain an excess of Mg, and increasing Mg uptake by the roots in some crops may be limited by competitive effects of other nutrients like Ca and K. It will be a sensible precaution to apply at least one foliar spray of Mg, at manufacturer's recommended rates, *if there have been clear visual symptoms of Mg deficiency in previous potato crops at the same site*. The symptoms are mainly that the older leaves turn yellow between the veins and eventually die back.

Calcium (Ca), sodium (Na), and sulfur (S)

Yield or quality responses to fertiliser applications of Ca and S have not been observed in New Zealand. Soils used for vegetables in New Zealand usually contain large quantities of Ca and S already. Both elements are commonly applied in other fertilisers. For instance, superphosphate contains appreciable amounts of Ca and S.

Do not apply Na fertilisers to potato crops in New Zealand.

Lime requirements

The available evidence suggests potato growers should keep soil pH in the range 5.2–6.0 but avoid liming in the 1–2 years preceding the crop especially if potatoes have been grown in the field previously and the pathogen common scab (*Streptomyces scabies*) is present. If there is a need to increase soil pH for other crops in the rotation, lime should be applied immediately after the potato crop is harvested.

Analysis of fertiliser response experiments suggests soil pH values between 5.2 and 6.3 do not affect potato yield in New Zealand. Values outside of this range have not been tested, but values above 6.5 can be expected to cause trace element deficiencies. The incidence and severity of common scab is increased in soils with pH above 5.2 (Lambert & Manzer 1991) and New Zealand pathologists recommend that soil pH should be kept <6 (Hedley & Close 1985).

Trace elements

Applications of trace elements to New Zealand potato crops are unlikely to generate an economic return, unless there is strong evidence that specific deficiencies have occurred on previous crops at that site. Offtakes are usually a few g/ha and availability of these nutrients is so dependent upon pH and changes in soil aeration (water content) that trace elements applied to the soil will usually be wasted. Potential exceptions could be B on sedimentary soils following a wet winter and spring, and Cu on organic soils. In those cases the best option may be a foliar spray applied in the early morning or evening at the manufacturer's recommended rates.

10.3. Maintenance nutrient applications

Total uptake of N and K can be very large (Table 10-1). Nutrient amounts in the shoots are considerable, and these are returned to the soil in crop residues, but the amounts potentially removed from the paddock in tubers remain large.

Table 10-1. Amounts of major nutrients removed from the soil by an 77 t/ha potato crop of the variety Fianna (Sher 1997). Nutrients in the tubers are removed from the paddock, the rest are recycled.

	N	P	K	S	Ca	Mg
Roots (kg/ha)	6.4	0.65	7.9	1.6	3.6	1.7
Shoots (kg/ha)	106	6.5	310	7.8	43	29
Tubers (kg/ha)	341	47	511	32	10	21
Total uptake (kg/ha)	454	54	828	42	57	51

Table 10-2. Offtakes of major nutrients for potato crops. These assume 80% of the tuber yield is removed from the paddock. Maintenance applications of N are not recommended except under organic production systems.

	N	P	K	S	Ca	Mg
kg/t tubers	3.4	0.47	5.1	0.32	0.10	0.21
Offtakes (kg nutrient/ha)						
Scenario 1: pot. yield 100 t/ha	273	37	409	26	8.3	16.6
Scenario 2: pot. yield 87 t/ha	237	32	355	23	7.2	14.4
Scenario 3: pot. yield 76 t/ha	208	29	312	20	6.3	12.7
Scenario 4: pot. yield 50 t/ha	135	18	202	13	4.1	8.2

Maintenance nutrient applications must be estimated from the kg of each element per tonne of tubers *removed from the paddock* (Table 10-2). If a crop yields 100 t/ha in the field and 80% of the tubers are removed then the offtake of P would be about 100 x 80/100 x 0.47 = 37 kg P/ha in the tubers.

Maintenance applications of any particular nutrient should be made only if none will be applied to grow the crop. For N, maintenance applications should be considered only under organic production systems using composts.

The calculated maintenance applications for P and K are large, possibly because the concentrations in Table 10-1 reflect some luxury uptake. Applying such large amounts of K is expensive and may pose risks for crop establishment and tuber quality. The maintenance recommendations here follow the strategy: (a) If QT K>12, do not apply any maintenance K; (b) If QT K<=12, apply half the calculated amount for the potential yield. If half maintenance rates are being applied, be sure to check the soil QT K at least a month before the next crop, and apply further K if the new QT value appears limiting for the next crop.

If Olsen P>70, do not apply any maintenance P (allow Olsen P to decrease).

For methods of application of nutrients follow the guidelines for nutrients to grow the crop.

10.4. Plant nutrient analysis

Some processing companies have large databases of information connecting petiole or sap nutrient concentrations and likely responsiveness to nutrients (especially N). Access to this information is not available outside of those companies. Petiole or sap nutrient tests are likely to be helpful only for growers with several years of experience gathering and interpreting such data for the same variety and growing locations.

Laboratories may quote typical or adequate nutrient concentrations in leaves, petioles or in the sap. These are difficult to interpret in terms of whether your crop needs more fertiliser applied. However, there is information for the optimal tuber nutrient contents at maturity (Table 10-3). This can be useful as part of a post-mortem on why a crop may not have yielded to potential, and the results may be useful for managing future crops.

Table 10-3. Optimum nutrient concentrations for potato tubers at harvest. Values are given on a dry mass (DM) basis (Greenwood et al. 1980b, c, d).

Nutrient	Optimum DM%
N	1.6
P	0.23
K	1.7

Most likely deficiency symptoms

Helpful images are available from the Yara CheckIT app for mobile telephones (Yara 2017), although the accompanying descriptions are sometimes at odds with New Zealand experience of where such deficiencies may occur. The most likely deficiencies are of N and P.

Table 10-4. Nutrient deficiency symptoms of potatoes under New Zealand conditions. The descriptions of symptoms are adapted from those of Wood et al. (1986), and Kumar (2015).

Nutrient	Symptoms	Notes
N, nitrogen	Weak growth, older leaves yellow and senesce early.	
P, phosphorus	Plant growth is stunted, and darker than normal. Older leaves develop necrotic spots. Some varieties may show unusual purpling of the stem, petiole and undersides of leaves.	*These are also symptoms of a number of other problems*, be cautious in diagnosing P deficiency from visual symptoms.
K, potassium	Older leaves bluish-green and may become bronzed and curl or crinkle. Areas between veins may develop spots and the leaf margins may scorch.	Rarely seen under New Zealand conditions, but mild K deficiency shows few visible symptoms.

Nutrient	Symptoms	Notes
S, sulfur	General yellowing of the leaves. May be some red colour to the veins, petioles and leaf undersides.	Rarely seen in New Zealand crops.
Ca, calcium	Thin stems and small terminal leaves with inward curling margins.	Extremely unlikely in New Zealand.
Mg, magnesium	Older leaves yellow between the veins and eventually die back.	No verified cases of Mg deficiency in potatoes in New Zealand.
B, boron	Stunted growth, growing point dies, and a general yellowing of the leaves.	Extreme symptoms similar to Ca deficiency, but rare in New Zealand.
Fe, iron	Young leaves become yellow but veins may remain green.	Only likely when soil pH is too high. May be difficult to distinguish from Mg or Zn deficiency.
Mn, manganese	Leaves develop brown spots along the veins. Growth severely decreased.	Rare in New Zeland.
Cu, copper	Generally slight yellowing of the leaves. Leaves curl and petioles may point downward.	May be associated with high soil pH, excessive soil water contents, or over-supply of other trace elements.
Zn, zinc	Yellow areas between the veins especially in the younger leaves.	Generally associated with high soil pH. May be difficult to distinguish from Mg or Fe deficiency.

11 Spinach, silverbeet and beetroot

Spinach (*Spinacia oleracea* L.), silverbeet or Swiss chard (*Beta vulgaris* L.), and beetroot (red beet, *Beta vulgaris* L.) are grown throughout New Zealand for the domestic market. Silverbeet, beetroot, fodder beet and sugar beet are varieties of the same species, although silverbeet varieties have been developed for harvesting of the leaf and stem rather than the swollen stems (“roots” or “bulbs”) of the others. Beetroot is occasionally grown so the leaves can be used in salads. Beetroot is grown for processing of the roots in Hawke’s Bay.

These crops are members of the *Chenopodiacea* family of plants that exhibits a strong ability for luxury uptake of nutrients – in other words given the opportunity they will accumulate more mineral nutrients than they need for maximum yield or quality. This can make it difficult to build nutrient recommendations based on nutrient budgets for target yields.

There have been few published descriptions of field crop responses to fertilisers in New Zealand (results from glasshouse experiments are of little use here). Those that are available and relevant here are referred to in the Fertiliser recommendations section.

11.1. Potential, field, and marketable yields

There are no suitable models available for potential yields of these crops. Nutrient recommendations are best based on target yields that should be limited to the best field yields obtained in each region for the same planting month. Even there it can be difficult to get consistent information.

For spinach, Williams et al. (2003) reported maximum yields of 6, 25 and 13 t/ha for crops planted at Pukekohe on 6 May 1996, 29 April 1997 and 19 May 1998, respectively. The fertiliser modelling analysis of two spinach experiments at Levin (Renquist et al. 1998) suggested field yields of 18 and 25 t/ha. There is some uncertainty about the plant populations in the experiments reported by both Williams et al and Renquist et al.

Norris et al. (2018) reported yields of 15–17 t/ha for baby spinach grown near Gisborne.

Silverbeet yields are poorly documented in New Zealand. The data of Aitken and Hewett (2016) suggests the industry average yield is about 18 t/ha. Wallace (2000) suggested very low yields for New Zealand (7.5–12.5 t/ha at 55,000–111,000 plants/ha). Both sources are presumably indicating the marketable yield after trimming, not the total field yield. Assuming that marketable (trimmed head) yield is 80% of the field yield then we could reasonably expect New Zealand crops to achieve field yields of 9–23 t/ha with current practices. Even so, these figures may underestimate what is possible. In Europe fresh field yields of up to 80 t/ha have been recorded for low populations (50,000/ha) given ample compost (Paredes et al. 2005), up to 46 t/ha at a plant population of 89,000/ha (Kolota & Czerniak 2010), and up to 52 t/ha at a population of 100,000/ha (Pokluda & Kuben 2002). Of course in practice yields will depend on market requirements for head size and leaf condition, and such details may differ considerably between the New Zealand and European markets.

For beetroot, in Hawke’s Bay root yields can be up to 100 t/ha, but usually factory and marketing requirements constrain maximum yields to be less than this. Beetroot leaves are sometimes harvested for salads and may be repeatedly harvested; total yields are not documented in New Zealand, but are unlikely to exceed 50 t/ha.

The recommendations here are based on the following field yields that growers may use as targets:

- *For spinach*, 15, 20, and 25 t/ha (up to 200,000 plants/ha). For baby spinach populations may be much higher, but yields will often be 15–20 t/ha.
- *For silverbeet* 10, 20, and 30 t/ha (up to 120,000 plants/ha). Variations in market requirements complicate the choice of target yield. A yield of 20 t/ha corresponds roughly to a 100,000 heads/ha at an average size of 250 g each after trimming.
- *For beetroot leaves*, 20, 30 and 50 t/ha (up to 600,000 plants/ha).
- *For beetroot roots 40, 60 and 80 t/ha (plants/ha varies from about 400,000 through to 1,400,000 depending on the target market, and whether it is a* main crop *or baby beetroot crop).*

Marketable yields will often be less than the above targets. For calculation of maintenance nutrient requirements here we have assumed 90% of the yield fits market requirements. Until potential yield and nutrient response models for these crops are available nutrient recommendations need to be based on a combination of likely uptakes, offtakes and target soil test values.

11.2. Nutrients to grow the crop

Soil tests

Before the crop is planted carry out soil testing for each paddock from 0–15 cm depth. Choose the standard soil testing suite (pH, Olsen P, QT Ca, K, Mg and Na, CEC and volume weight) PLUS 'Available N' (anaerobically mineralisable N, in kg N/ha).

Key point: Assumed soil bulk densities

The generic recommendations for spinach, silverbeet, and beetroot assume the bulk density in the field (ρ_{field}) is 1.0 g/ml and the bulk density of air-dried sieved soil in the laboratory (*volume weight*, ρ_{lab}) is 1.0 g/ml. These values can be used to make the nutrient recommendations below more specific to a site if measured values of ρ_{field} and ρ_{field} are known (see Chapter 2, PARJIB and soil bulk density).

Nitrogen (N)

Goh and Vityakon (1983) showed that yields of spinach increased as single applications of ammonium sulfate with a nitrification inhibitor rose to 300 kg N/ha. However, total N uptake by the crops was probably less than 125 kg N/ha, and there was no yield response if the N was applied as potassium nitrate (which would have been readily leached). Graph 2 of Wood (1997) appeared to show spinach responding to combined N and P applications up to 400 kg/ha of each nutrient, but no supporting details or statistical information was provided. Presumably based on this same data set, Wood et al. (1986) suggested N application rates of 350 kg N/ha for spinach grown in winter. Such large rates are now unjustifiable for winter crops. Williams et al. (2003) working with spinach at Pukekohe showed that high N application rates at planting are very inefficient and can lead to large amounts of nitrate leaching; it is much better to apply smaller N rates and split them over several applications to better match demands of the crop. For baby spinach grown near Gisborne, in a crop yielding 17 t/ha N uptake was 65 kg N/ha when 46 kg N/ha was applied as fertiliser; applying 89 kg N as fertiliser did not increase N uptake or yield (Norris et al. 2018).

Apart from the leaching risk there are other reasons to be wary of applying too much N fertiliser. First, yields of these crops can be decreased by applying more than the optimum amount of N (Goh & Vityakon 1983; Renquist et al. 1998; Webster 1969). Second, there is potential for a combination of very high N fertiliser rates and dull weather to raise nitrate concentrations in the edible plant portions to values that are of concern for human health (Cantliffe 1973; Goh & Vityakon 1986; Thomson et al. 2007).

Recommendations here are given on the basis of critical N concentrations in spinach and beetroot (Greenwood et al. 1980a). They assume no leaching of nitrate below the root zone and that the majority of the N available from the soil is in the top 15 cm depth, as estimated by the Available N (AMN) procedure. There are probable errors introduced by both assumptions, but they will tend to compensate for each other. Critical concentrations in the shoots *and* roots were included; for both spinach and silverbeet the critical N concentrations in the roots were assumed to be the same as Greenwood et al. (1980a) reported for beetroot. A root:shoot ratio of 0.2 was assumed for spinach, 0.5 for silverbeet and 1.0 for beetroot grown for leaves. For beetroot grown for root harvest, the root:shoot ratio was assumed to be 2.5, 3.5 and 5 for the target yields of 36, 54 and 72 t/ha. These values are based on observations made in unpublished experiments conducted by Plant & Food Research in Hawke's Bay (Hunt, A. *in preparation*).

Recommendations for the total amounts of N to apply are given in Table 11-1. The total amounts recommended should normally be split into three or more applications.

At planting:

- **Soluble and controlled-release N fertilisers** are best incorporated or (if planting arrangements permit) knifed in 2–5 cm from the plant row.
- **If using controlled-release N fertilisers,** apply up to 100 kg N/ha of the controlled-release product and up to 20 kg N/ha of a soluble N fertiliser.
- ***If using only soluble N fertilisers*** like urea, ammonium sulfate, or CAN, apply no more than 20 kg N/ha, or up to 50 kg N/ha if this is a winter-planted crop and wet weather will greatly limit opportunities for side-dressing in the second and third months of growth.

Split the remainder of the recommended N across at least two side-dressings after the plants have at least two true leaves (direct-seeded crops). Avoid applying more than 50 kg N/ha at any one time. Side-dressings may be broadcast (if possible just before light rain or irrigation), but be careful to avoid fertiliser lodging amongst the leaves where it can cause cosmetic damage.

If applying N in the form of composts, incorporate these at least 2 weeks before planting.

Table 11-1. Recommended N fertiliser rates for spinach, silverbeet, and beetroot. The values are calculated from the critical concentrations of N needed in the crops for maximum yield.

	Spinach			Silverbeet			Beetroot leaves			Beetroot roots		
Target yield (t/ha)	15	20	25	10	20	30	20	30	50	40	60	80
Available N (kg N/ha)												
30	40	65	90	10	40	75	60	105	195	130	185	240
60	10	35	60	nil	10	45	30	75	165	100	155	210
90	nil	5	30		nil	15	nil	45	135	70	125	180
120		nil	nil			nil		15	105	40	95	150
150								nil	75	10	65	120
180									45	nil	35	90
210									15		10	60
240									nil		nil	30
270												nil

Phosphorus (P)

For spinach, three different target Olsen P values (35, 110 and 34 ppm) have been published (Prasad et al. 1988). Each of these was based on only five data points and the quality of that information was not clear. Results from the modelling analysis of Renquist et al. (1998) imply a target Olsen P of 30–40 ppm when maximum yield is in the range 18–25 t/ha. For beetroot with a maximum yield of about 40 t/ha, Prasad et al. (1988) identified a target Olsen P of about 40 ppm. All those target values assume fertiliser P is broadcast. Silverbeet and beetroot are the same species, and we must assume they respond similarly to P supply. For spinach, silverbeet, and beetroot the recommended strategy is to use a two-step combination of broadcast and carefully banded starter P fertilisers:

If Olsen P <35 µg/mL, apply sufficient P fertiliser to raise the Olsen P to 35. The rate depends on the soil type and can be calculated using the rules in Chapter 2 *(*To raise soil Olsen P).

Reserve up to 20 kg P/ha of this total to apply as a starter fertiliser. If direct seeding, apply the fertiliser down the spout providing this enables some separation of seed and fertiliser; alternatively, if planting arrangements allow, then knife the starter P in 2–5 cm from the plants. For baby spinach or baby beetroot crops P fertiliser may have to be broadcast and incorporated ahead of planting. If soil ASC (P retention) is >40% then the efficiency of broadcast starter P fertiliser will be low; try to find ways of applying it in bands or incorporating it shallowly (say to only 5 cm).

The remainder (if any) of the recommendation should be applied as a capital or base dressing before planting. This fertiliser should be broadcast and incorporated to 15 cm depth.

Potassium (K)

Previous recommendations (Wood et al. 1986) identified target QT K values ranging from 8 in sand through to 15 in clays, assuming the K was broadcast. There are no published experimental data relating performance of these crops to soil QT K or even to exchangeable K concentrations, so it is difficult to appraise what those previous recommendations were based on, and the basis for distinguishing target K levels on the basis of soil texture. The recommendations here are a combination of broadcast and banded fertilisers using a target QT K of 10.

For spinach, silverbeet and beetroot the recommended strategy is to use a two-step combination of broadcast and carefully banded starter K fertilisers. We must assume silverbeet and beetroot responds similarly to K supply.

If QT K <10, apply sufficient K fertiliser to raise QT K to 10. The rate depends on the soil type and can be calculated using the rules in Chapter 2 (To raise soil QT K).

- Reserve a portion of the total to apply as a starter fertiliser. SOP will be safer to use for this than MOP. If direct seeding, apply up to 15 kg K/ha down the spout provided there is some separation of seed and fertiliser. Alternatively, knife in up to 30 kg K/ha as a narrow band 2–5 cm from the seed.

- The remainder of the recommendation should be applied as a capital or base dressing at least 4 weeks before planting. Broadcast and incorporate it to 15 cm depth. Use the cheapest form of K fertiliser you have available (usually MOP).

Magnesium (Mg), sodium (Na), sulfur (S) and trace elements

There is no evidence that in New Zealand yield of the spinach, silverbeet or beetroot will respond to fertiliser applications of Mg, Na, or S, although the plants have a strong capacity for luxury uptake of those nutrients. Taste of the leaves in particular might by affected by such luxury uptake, but little has been published, to base recommendations on.

Applications of trace elements to these crops are unlikely to generate an economic return, unless there is strong evidence that specific deficiencies have occurred on previous crops at that site. Offtakes are of the order of a few g/ha and availability of these nutrients is so dependent upon changes in soil aeration (water content) and pH that fertiliser applications to the soil will usually be wasted. Potential exceptions could be B for beetroot grown on sedimentary soils following a wet winter and spring, and Zn for spinach grown on soils with pH values >6.5. In those cases the best option may be a foliar spray applied in the early morning or evening at the manufacturer’s recommended rates.

Calcium (Ca) and lime

Yield and quality responses to Ca applications are unlikely in New Zealand as most horticultural soils contain an excess of this nutrient already. There have been no published experiments measuring yield response to soil pH values, so we recommend following the earlier directions of Wood et al. (1986).

Spinach: Apply lime if pH is less than 5.6, targeting a pH of 6.2.

Silverbeet and beetroot: Apply lime if pH is less than 6, targeting a pH of 6.5.

Apply fine lime at least a month before planting.

11.3. Maintenance nutrient applications

Typical concentrations of nutrients in spinach and beetroot are given in Table 11-2.

Table 11-2. Estimated concentrations of N, P and K in spinach and beetroot at harvest. The data are taken from the USA (USDA 2018) and are given as kg nutrient per tonne of yield.

Plant part	N	P	K
Spinach (whole shoot)	4.9	0.5	5.3
Silverbeet leaves	2.9	0.5	2.4
Beetroot leaves	4.4	0.5	7.5
Beetroot roots	2.7	0.4	3.1

Maintenance requirements are estimated by multiplying the target or expected yield by the concentrations in kg nutrient per tonne of yield in Table 11-2. Estimated concentrations of N, P and K in spinach and beetroot at harvest. The data are taken from the USA (USDA 2018) and are given as kg nutrient per tonne of yield. Representative offtakes calculated in this way are given in Table 11-3.

Maintenance applications of any particular nutrient should be made only if none will be applied to grow the crop. For N maintenance applications should be considered only under organic production systems using composts.

Maintenance P should be broadcast and incorporated in advance of planting. Do not apply maintenance P if soil Olsen P>50.

K maintenance applications should be applied as a capital or base dressing. Broadcast and incorporate it to 15 cm depth at least 4 weeks before planting, using the cheapest form of K fertiliser you have available (usually MOP). If the applications are made closer to planting then use SOP.

The calculated maintenance applications of K are large, especially for beetroot. Applying such large amounts before or at planting is expensive and may pose risks for crop establishment. Furthermore, provided QT K is >6, most New Zealand soils contain large reserves of K. The recommendations for K maintenance applications follow the strategy: (a) Apply half the calculated amount for the expected yield; (b) Check the Soil QT K at least a month before the following crop, (c) Apply further K fertiliser if the new QT value appears limiting for the next crop.

If QT K>12, do not apply any maintenance K.

Table 11-3. Offtakes of N, P and K by spinach, silverbeet, and beetroot crops calculated using USDA data for crop composition. These values assume 90% of the field yield is marketable.

	Field yield fresh (t/ha)	N	P	K
Spinach	15	66	7	72
Spinach	20	88	9	95
Spinach	25	110	11	119
Silverbeet	10	26	5	22
Silverbeet	20	52	9	43
Silverbeet	30	78	14	65
Beetroot, leaves	20	79	9	135
Beetroot, leaves	30	119	14	203
Beetroot, leaves	50	198	23	338
Beetroot, roots	40	97	14	112
Beetroot, roots	60	146	22	167
Beetroot, roots	80	194	29	223

The calculated offtakes for N, P and K generally agree well with values calculated assuming the crops contain just the critical nutrient concentrations for maximum yield. For beetroot leaves the calculated offtakes of K are about 50% larger than if the plants contained just the critical concentrations for maximum yield; this is understandable if there has been luxury uptake in the crops that the USDA data is based on. However, for beetroot roots the calculated N, P and K offtakes are about 70% of the values calculated from critical nutrient concentrations. The reasons for this discrepancy are unknown at present. For present purposes the K maintenance strategy recommended above will safeguard soil resources without compromising yields.

11.4. Plant analysis

Published concentrations of nutrients in New Zealand crops are few and scattered. The values held in the databases of the commercial laboratories are difficult to interpret because of the risk of luxury uptake. Critical nutrient concentrations have been carefully measured for spinach and beetroot crops in the UK; for present purposes assume that concentrations for silverbeet are the same as those for beetroot. The critical concentrations decrease as the plants get bigger (Table 11-4).

These values are very useful benchmarks for diagnosis of N, P and K deficiencies. If plant analysis indicates values below the ranges given here, then there is a substantial risk the crop is suffering from a nutrient deficiency.

Table 11-4. Critical concentrations of N, P, and K in spinach and beetroot (Greenwood et al. 1980a). The critical concentrations are given as % dry matter.

Plant part	Dry mass (g/plant)	Fresh mass (g/plant)	N	P	K
Spinach (whole shoot)	0.52	5.2	5.1	1.4	8
Spinach (whole shoot)	8.0	80	4.4	0.45	5.1
Beetroot (whole shoot)	1.3	13	3.9	0.51	6.8
Beetroot (whole shoot)	14	140	2.4	0.49	1.6
Beetroot (root)	1.4	14	2.5	0.47	3.7
Beetroot (root)	10	77	2.1	0.45	3.1
Beetroot (root)	39	300	1.4	0.43	2.4

Most likely deficiency symptoms

Excellent images of these were published by Scaife and Turner (1983). Helpful images are also available from the Yara CheckIT app for mobile telephones (Yara 2017).

Table 11-5. Nutrient deficiency symptoms of spinach, silverbeet and beetroot grown in the field under New Zealand conditions. The descriptions of symptoms are adapted from those of Wood et al. (1986).

Nutrient	Symptoms	Notes
N, nitrogen	Yellowing of the older leaves	
P, phosphorus	General reduction in growth	
K, potassium	Old leaves loose turgor and dies back from tip (silverbeet and beetroot) Papery dead patches and flaccid tips of leaves (spinach).	Rarely seen under New Zealand conditions, except perhaps on shallow sandy soils, but moderate K deficiency shows few visual symptoms and can restrict yields.
S, sulfur	Young leaves narrow, stiff and erect. yellowing and profusion of purple spots (beetroot). Older leaves have dead patches near tips (spinach).	Rarely seen in New Zealand crops, perhaps because many commonly used P and K fertilisers contain S also. Purple spots can have other causes.
Mg, magnesium	Red mottles leading to brown blisters between the leaf veins of the older leaves.	No verified cases of Mg deficiency in spinach, silverbeet or beetroot crops reported in New Zealand.
Fe, iron	Bleaching of new leaves.	May be associated with high soil pH, excessive soil water contents, or over-supply of other trace elements such as Mn or Cu.
Zn	Scorched papery tissue near tips of young leaves, and between veins of older leaves.	Hard to diagnose visually, generally associated with high soil pH.
B	Spotted lesions in root flesh sometimes with large black areas on root surface (beetroot). New leaves stubby and necrotic older leaves die back from tips, bubbled appearance of new leaves on mature plants (spinach).	Many New Zealand soils may be borderline in B supplying ability, but B toxicity is easily induced by over-zealous application of B.

12 Sweet corn

Sweet corn is the same species as maize (Zea mays L.). Sweet corn is grown throughout the country, but most commercial crops are in Canterbury, Marlborough, Hawke's Bay, Gisborne, Waikato and Bay of Plenty. Sweet corn has a less vigorous root system than its cousin maize (Aslam 2005) – which makes it less capable of extracting nutrients from the soil. On the other hand, it is harvested well before maize and so requires less nutrient uptake.

Surveys of commercial crops in Hawke's Bay and Gisborne in 1998–99 and 1999–2000 indicated that even after accounting for planting date and plant population 70% lost yield because of insufficient or poorly-timed irrigation, and 84% of them lost yield because of inadequate nutrition. The nutrients most usually in short supply were nitrogen and phosphorus.

It is important to remember that supplying all the nutrients required to achieve potential yields may not be economic – and this is especially the case if the crop is likely to be under- or over-irrigated. Extra fertiliser will not compensate for insufficient irrigation.

12.1. Potential yields

In each region, potential yields can vary substantially with variety, planting date and the achieved plant population. The greatest potential yields are for early-sown crops and can be as high as 40 t/ha (of ears or cobs at 72% moisture plus wrapper leaves). Achieved yields rarely reach this especially because early planting risks frost damage, established plant populations are rarely optimal, and because processing and marketing schedules must include later planting dates. Field yields are often in the range 20–30 t/ha.

Here we consider primarily situations where yield is measured in the mass of ears. For fresh market and some processing situations, grading standards for marketable ears have a big impact on yields because for single picks the secondary (or tertiary) cobs may be discarded if they are too small. If the intended product is stripped kernels then these secondary and tertiary ears may contribute to the total yield provided they meet other quality criteria (like dry matter % and colour). More information on potential yield of sweet corn, water stress effects and quality issues can be found in Hunt et al. (2017) and Reid (2016a, 2016b).

Nutrient recommendations are given for two scenarios:

Scenario 1: Potential yield of 20 t/ha of fresh ears. This is typical for short-duration hybrids, and for late- or medium-duration hybrids planted in especially warm regions north of the Bay of Plenty. For nutrient maintenance calculations, 80% of the field yield is assumed to be removed from the field (16 t/ha).

Scenario 2: Potential yield of 30 t/ha of fresh ears. This is typical for early-planted crops of medium to long duration hybrids in Gisborne, Hawke's Bay, Marlborough and Canterbury. For nutrient maintenance calculations, 80% of the field yield is assumed to be removed from the field (24 t/ha).

Where it is more appropriate to consider yield in numbers rather than mass of ears the above yields will have to be divided by the target average mass of a marketable ear as defined by the intended market. Similarly, kernel yields for some processing uses have to be calculated from the above ear yields multiplied by a kernel recovery factor supplied by the processor.

12.2. Nutrients to grow the crop

The recommendations for N, P, K and Mg are based on work carried out at 17 different sites in New Zealand from 1996 to 2000. The experiments covered a wide range of combinations of fertiliser rates, potential yields, and planting densities. The results from all sites were collated and analysed together by fitting the PARJIB model (Reid 2002; Reid et al. 2002c). The model fitted the data well. The model's predictions for P responses match well with the observations of Prasad et al. (1988). Both the model and Prasad et al.'s results suggest strong yield responses to P fertiliser if soil Olsen P is <20 µg/mL. However, Aslam (2005) conducting experiments in Hawke's Bay and the Manawatu found no evidence that sweet corn or maize yields responded to P fertiliser when Olsen P was as low as 10 µg/mL. Aslam's results suggest that sweet corn responses to P fertiliser are unlikely on most horticultural soils. Further work is needed to reconcile these conflicts. The wider range of experimental conditions covered in the PARJIB analysis means that for present purposes it is safer to base P recommendations on the model results.

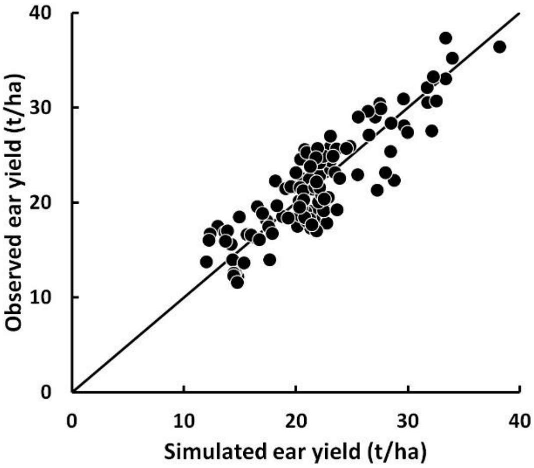


Figure 12-1. Performance of the PARJIB model for sweet corn ears yields. Measured ear yields are plotted against the simulated values from the model after calibration. The data comes from measurements made at 17 different sites from 1996 to 2000. The plotted line is the line of perfect agreement.

Soil tests

Before the crop is planted carry out soil testing for each paddock from 0–15 cm depth. Choose the standard soil testing suite (pH, Olsen P, QT Ca, K, Mg and Na, CEC and volume weight) PLUS 'Available N' (anaerobically mineralisable N, in kg N/ha).

Key point: Assumed soil bulk densities

The generic recommendations for sweet corn assume the bulk density in the field (ρ_{field}) is 1.15 g/ml and the bulk density of air-dried sieved soil in the laboratory (*volume weight*, ρ_{lab}) is 0.88 g/ml. These values can be used to make the nutrient recommendations below more specific to a site if measured values of ρ_{field} and ρ_{field} are known (see Chapter 2, PARJIB and soil bulk density).

Nitrogen (N)

When available N is low, yield responds strongly to N fertiliser, but it is a "diminishing returns" style of response.

Key point: Previous land use

If the soil has been under healthy pasture continuously for the previous 2 years *apply no N fertiliser.* Ensure the pasture residues are cultivated into the soil and kept moist for at least a month before planting.

If using a slow release form of N fertiliser or composts, broadcast and incorporate these before or at sowing.

If using soluble, solid, N fertilisers (like urea), remember that generally N applied before planting is at risk of leaching. Around Gisborne that risk is slight and the N can be broadcast and incorporated just before or after planting. In other regions avoid applying N before planting and *split the recommended N fertiliser into two applications*, one at planting and the majority applied as a side-dressing 4–6 weeks later (preferably just as stem elongation begins).

For side-dressing knife the fertiliser in no closer than 10 cm from the plants. Side-dressings simply placed on the soil surface risk significant volatilisation losses.

If fertigation is available, spread the N applications between crop emergence and the start of stem elongation.

Soil Available N (kg N/ha)	Recommended N application (kg N/ha) to grow the crop	
	Scenario 1: Potential yield about 20 t/ha fresh ears	Scenario 2: Potential yield about 30 t/ha fresh ears
50	180	250*
80	100	240
100	40	180
110	20	160
120	nil	130
150		40
160		20
170		nil

* responses to more N may occur but be uneconomic.

Phosphorus

Aslam (2005) measured total P uptake of 32 and 18 kg P/ha by sweet corn crops growing in Hawke's Bay and the Manawatu respectively. The lower P uptake in the Manawatu experiment may have been due to dry soil conditions.

Use the most rapidly available form of P that is available and suitable for your growing system. Base or capital dressings can be broadcast before planting, but make sure that up to 10 kg P/ha of the recommended application is placed down the spout at planting. Larger amounts can be knifed in 50–100 mm from the drill line, again at or very soon after planting. *Do not side-dress growing crops with P because this will be poorly taken up by the crop.*

Soil Olsen P (µg/mL)	Recommended P application (kg P/ha) to grow the crop	
	Scenario 1: Potential yield about 20 t/ha fresh ears	Scenario 2: Potential yield about 30 t/ha fresh ears
10	80	up to 140
20	20	80
25	nil	60
30		40
35		nil

Potassium

Generally, K fertiliser applications are not economic for short-duration sweet corn crops, unless the soil is severely depleted in K. Use the cheapest source of readily available K that you have available. Apply K fertilisers by broadcasting and incorporating before planting.

QT K	Recommended K application (kg K/ha) to grow the crop	
	Scenario 1: Potential yield about 20 t/ha fresh ears	Scenario 2: Potential yield about 30 t/ha fresh ears
3	60	180
4	nil	120
5		40
6		nil

Magnesium

Yield or quality responses to Mg applications are unlikely in New Zealand. Fertiliser Mg applications Mg have been tested at sites with Mg QT values down to 13 but no crop responses were observed. Maintenance applications are not recommended unless the Mg QT value falls below about 13.

Calcium (Ca), sodium (Na), and sulfur (S)

Do not apply Na to sweet corn crops in New Zealand. It is very unlikely the crop will respond directly to applications of Ca or S. Soils used for vegetables in New Zealand usually contain large quantities of Ca and S already. Both elements are commonly applied as part of other fertiliser applications. For instance, superphosphate contains appreciable amounts of Ca and S. Lime also contains a large amount of Ca.

Lime

Apply lime if pH is less than 5.5, targeting a pH of 6.0. Soil pH values as low as 5.5 do not appear to affect yield, but values appreciably above 6.5 may cause trace element deficiencies.

Trace elements

In New Zealand there has been little research on the effect of trace elements on sweet corn crops. Serious trace element deficiencies are rarely identified in sweet corn or maize crops. Overseas research has reported trace element deficiencies and made some recommendations for sweet corn. In many cases, deficiencies are most likely to be caused by an unsuitable soil pH affecting trace element solubility rather than there being inadequate amounts actually in the soil.

Sweet corn has relatively high demand for Zinc (Zn) compared with other trace elements. Deficiency of Zn may occur in alkaline soils (pH > 7.0) and sandy soils. The risks in such situations are increased if the soil Olsen P is greater than about 30 µg/mL because that may discourage the plants to form mycorrhizal symbioses that greatly help Zn uptake (Zhang et al. 2017). If Zn deficiency is suspected (see the section below

Most likely deficiency symptoms) then the best solution is to apply a foliar Zn spray containing at manufacturers recommended rates.

Lowering soil pH can increase Zn availability to the point of toxicity – but we are not aware of this happening in New Zealand. Zn deficiency can lead to iron deficiency which also causes similar symptoms.

Sweet corn may perform badly in poorly drained soils when there is too much rain or irrigation leading to trace element toxicities. Poor soil aeration increases the solubility of many trace elements, and excessive uptake of copper (Cu), manganese (Mn), Fe and Zn is probably more common than deficiencies of these nutrients.

Occasionally plants show iron (Fe) deficiency even when they have taken up plenty of the element. In 2007, we found visual symptoms of Fe deficiency in a sweet corn crop, but plant analysis revealed there was a lot of Fe in the leaves. The paddock was poorly drained and waterlogging seemed to have increased uptake of Fe and copper (Cu) to the point where Cu toxicity prevented the plants using the Fe properly.

12.3. Maintenance nutrient applications

The nutrients taken up in the largest quantities by sweet corn crops are N, P and K. The table below shows the approximate amounts of these elements that can be removed from the soil by a sweet corn crop. These were reported by Wood et al. (1986), but the provenance of that information was not defined, and there are reasons to be cautious that the figure for N is an overestimate (it equates to 220–272 kg N/ha total uptake by crops yielding 20–25 t/ha). First, the total uptake of N is greatly in excess of K, whereas in many crops the two are close (Greenwood & Stone 1998). Second, Aslam (2005) measured total N uptake of 161 kg N/ha by a sweet corn crops grown in the Manawatu and yielding 28 t/ha of total cobs. Third, Hanly and Gregg (2004) reported total N uptake of 100–125 kg N/ha for sweet corn crops yielding 17–20 t/ha (this excludes one treatment that yielded <10 t/ha). Finally, Figure 3.1 of Hansen (2000) indicates total N uptake of 2–3.3 g/plant corresponding to 140–240 kg N/ha for ear yields in the range 20–25 t/ha.

Table 12-1. Typical amounts of N, P, and K removed from the soil by a sweet corn crop yielding 16 t/ha of ears (Wood et al. (1986). The nutrients in the ears are removed from the paddock, the rest are recycled when the crop residues are incorporated.

		N	P	K
Plant (stems, leaves)	kg/ha	112	13	84
Ears	kg/ha	62	9	34
Total	kg/ha	174	22	118

Maintenance requirements are estimated by multiplying tonnes of ears removed from the paddock by the concentrations in kg nutrient per tonne of yield in Table 12-2. The maintenance K application for crop where 24 t/ha of ears were removed from the paddock would be 24 x 2.1 = 50 kg K/ha. Representative offtakes calculated this way are given in Table 12-2.

Table 12-2. Typical nutrient offtakes by sweet corn crops. Uptake and removal figures for Mg and S are not available for New Zealand crops, but they will be less than the values given for P.

	N	P	K
kg/t ear yield	3.9	0.56	2.1
Offtakes (kg/ha)			
Scenario 1: removed yield 16 t/ha	62	9	34
Scenario 2: removed yield 24 t/ha	93	14	51

- Maintenance applications of any particular nutrient should be made only if none will be applied to grow the crop. For N maintenance applications should be considered only under organic production systems using composts.
- Maintenance P should be broadcast and incorporated in advance of planting. Do not apply maintenance P if soil Olsen P>40.
- K maintenance applications should be applied as a capital or base dressing. Broadcast and incorporate it to 15 cm depth at least 4 weeks before planting, using the cheapest form of K fertiliser you have available (usually MOP). If the applications are made closer to planting, use SOP.
- Do not apply maintenance K if QT K>10.

Plant analysis

In maize the critical nutrient concentrations (in the whole plant) required for maximum growth are well-established, at least for N and P. They usually decrease as the plant gets bigger. We are not aware of any critical nutrient dilution curves for sweet corn, which may differ from maize in its ability to take up nutrients (Aslam 2005). Generally, leaf analysis is recommended only if deficiencies are suspected, because of complications due to the effect of whole plant size and age on leaf concentrations. However, useful values for comparison do exist for the ear-leaves over a narrow time span (Table 12-3). If deficiencies are suspected, take samples of the whole leaf around the primary ear at the tasselling to initial silking stage. This analysis will help you to identify the effectiveness of the fertilising schedule for this and the next crop. A difficulty is that usually the results arrive rather late for you to apply fertiliser if there is a deficiency. Often the only options are expensive – applying a foliar fertiliser or a solid by helicopter.

The Table below shows the currently accepted adequate levels for sweet corn.

Table 12-3. Critical leaf nutrient concentrations for sweet corn. These are given on a dry weight bases for the ear leaf at silking (Piggot 1986). Values are not available for sulfur (S) or sodium (Na).

Nutrient		Critical concentration
Nitrogen (N)	%	3.0
Phosphorus (P)	%	0.25
Potassium (K)	%	1.9
Calcium (Ca)	%	0.4
Magnesium(Mg)	%	0.25
Copper (Cu)	µg/mL	5
Zinc (Zn)	µg/mL	20
Iron (Fe)	µg/mL	50
Boron (B)	µg/mL	5

Most likely deficiency symptoms

See Table 12-4. Excellent images of these were published by Scaife and Turner (1983). Helpful images are also available from the Yara CheckIT app for mobile telephones (Yara 2017), although the accompanying descriptions are sometimes at odds with New Zealand experience of where such deficiencies may occur.

Table 12-4. Nutrient deficiency symptoms of sweet corn grown in the field under New Zealand conditions. The descriptions of symptoms are adapted from those of Wood et al. (1986).

Nutrient	Symptoms	Notes
N, nitrogen	Pale green leaves (especially the lower leaves).	
P, phosphorus	Small plants with uniform purpling of leaves.	Cold weather can cause similar discolouration and will not be avoided by applying P fertiliser. Some varieties have occasional plants with purpling on leaves that is not stress related.
K, potassium	Scorching of leaf edges; rolling of leaves resembling drought.	Rarely seen under New Zealand conditions, except perhaps on shallow sandy soils, but moderate K deficiency shows few visual symptoms and can restrict yields.
S, sulfur	Pale green-yellow leaves (especially the younger leaves); old leaf bases may be red.	Rarely seen in New Zealand crops, perhaps because many commonly used P and K fertilisers contain S also.
Ca, calcium	Dead tips of new leaves or tips fail to emerge; tips of several leaves may be joined together; leaf edges serrated or curled.	Extremely unlikely as New Zealand soils have ample available Ca. Some of the apparent symptoms may be due to insect damage of young plants.
Mg, magnesium	Yellow stripes between the leaf veins of the older leaves followed by red or purple colours on tips and edges.	No verified cases of Mg deficiency in sweet corn crops reported in New Zealand.
Fe, iron	Yellow striping of new leaves which may become bleached.	May be associated with high soil pH, excessive soil water contents, or over-supply of other trace elements such as Mn or Cu.
Zn	Broad bands of pale tissue in the lower half of emerging leaves; stem nodes reddish brown; small leaves and stunted plants.	Generally associated with high soil pH.
B	Thick brittle leaves with many raised stripes; short internodes; poor pollination; barren or partly barren ears with pointed tips.	Many New Zealand soils may be borderline in B supplying ability, but B toxicity is easily induced by over-zealous application of B.

13 Tomatoes for processing

There has been a great deal of research on the mineral nutrition of tomatoes (*Lycopersicon esculentum* Mill.). Much of that has concentrated on salad tomatoes where the fruit are harvested sequentially as they begin to ripen. Lessons from that research are often highly relevant to field tomatoes grown for processing. However, care must be made in interpreting the information because process tomatoes are harvested in a once-over mechanical operation, and fruit may have a wide range of ages and maturities.

In New Zealand, tomatoes are grown for processing mainly in Hawke's Bay and Poverty Bay. This geographical concentration brings with it some important differences from other vegetable crops. In particular, the soils are often heavy textured, and typically they have large concentrations of exchangeable calcium (Ca) and magnesium (Mg). These ions appear to affect the availability of potassium (K) for tomatoes much more than for other vegetables grown in New Zealand, and K supply is very important for achieving good tomato yields and quality.

Water stress (from deficits and surpluses) is another important aspect of field tomato production in New Zealand. Usually, tomato crops are irrigated in Hawke's Bay but not in Poverty Bay, but both regions usually experience marked summer drought. If yield is reduced by water deficits then nutrient requirements will be too. Overseas experience is that field tomato yields are very sensitive to water deficit, but experiments in Hawke's Bay often show no response to irrigation. This has been interpreted in terms of water moving up into the root zone from relatively shallow water tables in some of the heavier soils (Burgmans et al. 1998). Integrated field and modelling studies on tomatoes in Hawke's Bay have added another twist though – tomato yield is sharply reduced by the sorts of water excesses that readily occur if the crops are irrigated too much or if there is heavy rainfall (Reid et al. 2000a). Final yield may decrease by 0.5–2.0% for every day that the soil is wetter than field capacity. Yield losses due to excessive water supply rarely reduce the crops' needs for nutrients because they typically occur late in the season rains after much of the nutrient uptake has occurred.

13.1. Potential and field yields

Through much of the 1980s and 90s typical yields in New Zealand were around 70–100 t/ha. It now appears that for most crops the potential yield is much higher, around 150 t/ha (that is total fruit yield in the field, before deductions). Field yields are rarely this high, mainly because of the effects of deficits or surpluses of water, sometimes because soil structure is poor, and there may be necessary compromises associated with the date of harvest. Further contributing factors may include nutrient stresses limiting growth. Excessive or inadequate nutrient supply may contribute to further losses because of increased disease pressure in dense canopies and mixed fruit maturity.

Recommendations are made here for two scenarios:

Scenario 1: Potential and field yield both 150 t/ha. This is typical for most of the tomatoes grown in Hawke's Bay provided that irrigation is scheduled and applied carefully. After allowing for fruit left behind by the harvester and factory grading, marketable yields might be up to 120 t/ha.

Scenario 2: Field yield 120 t/ha due to water stress. Here water deficits are sufficient to reduce yield by 20% from a potential value of 150 t/ha. This is representative of most tomato crops in Poverty Bay and some in Hawke's Bay. Marketable yields might be up to 85 t/ha.

For both scenarios, maintenance nutrient rates have been calculated assuming 80% of the crop is removed from the field.

13.2. Nutrients to grow the crop

These are based on research carried out in Hawke's Bay by Crop & Food Research (now Plant & Food Research) and paid for by Heinz Wattie's Ltd (Reid & Kale 1997; Reid et al. 2000a; Reid et al. 2004). Crop and soil measurements from 33 different sites (including fertiliser trials and crop monitoring sites) were used to develop a variant of the PARJIB model for crop responses to nutrient supply (Reid 2002). In addition to nutrient supply, this version of the model accounted for the effects on yield of plant population, water deficit and excess, and infection by a limited number of diseases.

It is important to get the soil tested before each crop, and base fertiliser decisions on the soil test results for each paddock individually.

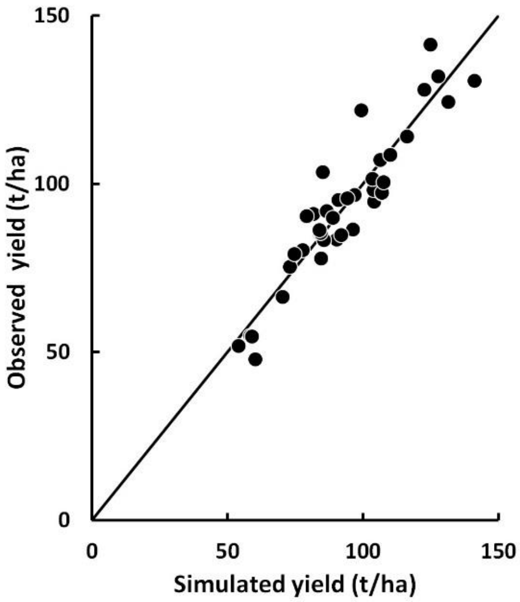


Figure 13-1. Performance of the PARJIB model for field tomatoes. Measured gross fruit yields are plotted against the simulated values after model calibration. The plotted line is that for perfect agreement. Each data point is a mean from 2–4 replicate field plots.

Soil tests

Before the crop is planted start the process of nutrient management with soil testing from 0–15 cm depth. Choose the standard soil testing suite (pH, Olsen P, QT Ca, K, Mg and Na, CEC and soil volume weight) PLUS 'Available N' (anaerobically mineralisable N, in kg N/ha)

Key point: Assumed soil bulk densities

The generic recommendations for process tomatoes assume the bulk density in the field (ρ_{field}) is 1.1 g/ml and the bulk density of air-dried sieved soil in the laboratory (*volume weight*, ρ_{lab}) is 0.84 g/ml. These values can be used to make the nutrient recommendations below more specific to a site if measured values of ρ_{field} and ρ_{field} are known (see Chapter 2, PARJIB and soil bulk density).

Nitrogen (N)

Unless soil structure is poor, tomato roots may grow beyond 70 cm depth. This makes them very effective at taking up N within the soil profile. Process tomato crops can take up large amounts of N over a long growing season, but the available evidence suggests this is not always best for yield. A survey of N fertiliser use was carried out on 27 process tomato crops in Hawke's Bay in 1997–99 (Reid et al. 2000b; Reid et al. 2001). The data from that survey were reanalysed for this book. Field yields ranged from 58 to 142 t/ha and the crops had received an average of 56 kg N/ha as fertiliser (range 0–120 kg N/ha). After harvest the soils contained an average of 80 kg N/ha of residual mineral N – so it seems at many sites there was much N applied that the crops did not take up or was surplus to the natural supply from mineralisation in the soil. Residual N values as large as this increase the risk of substantial nitrate leaching in the winter months unless a catch crop is planted very soon after harvest. For those site nitrate leaching was very small, because catch crops were planted and the following winters were unusually dry.

If using solid fertiliser and the Available N value is <50 kg N/ha apply half of the recommended fertiliser N at or soon after planting, banding it near the plants (but not closer than 5 cm). Side-dress the rest before flowering; knife in the N, no closer than 10 cm from the plants. Calcium ammonium nitrate is often used, but there is no strong evidence that this is better for tomatoes than cheaper products like urea.

Key point: Ration N for tomatoes

An ample supply of N encourages leaf growth. That is important to support growth of the fruit. *But too much N will decrease fruit yield.* Late in the season surplus N encourages leaf growth and it prolongs flowering and setting of more young fruit. All this happens when growers want the crop to be maturing the larger, early-set fruit – but instead these may rot or fall off before the whole canopy is ready for harvest.

If applying N in the form of composts, incorporate these at least 2 weeks before to planting, preferably during bed-formation.

If fertigation is available, split the recommended N fertiliser applications from establishment through to flowering.

Available soil N (kg N/ha)	Recommended N application (kg N/ha) to grow the crop	
	Scenario 1: Potential and field yield 150 t/ha	Scenario 2: Field yield 120 t/ha
30	90	70
40	70	50
50	50	20
60	30	20
70	20	nil
80	20	
100	nil	

Nitrogen and fruit quality

The percentage of green fruit at harvest increases with the amount of N supplied to the crop. Measurements made in 1996–97 suggested that provided the crop was not deficient in N, every 33 kg N fertiliser applied per hectare increased the green fruit % by one unit (Reid & Kale 1997). The same experiments indicated that applications of N fertiliser can slightly reduce tomato paste viscosity (applications of about 200 kg N/ha were needed to increase the standard Bostwick scale value by 1 cm).

Phosphorus (P)

If P fertiliser is required, apply up to 10 kg P/ha as a starter under the transplant or banded or knifed in no closer than 5 cm to the planting line. The remainder (if any) of the recommendation can be broadcast and incorporated pre-planting. For tomatoes in Hawke's Bay and Poverty Bay, banding of P fertiliser is slightly more effective than broadcasting, but the total P application may be too large for banding using superphosphate or compound fertilisers with a similarly small %P.

Side-dressings of P are unlikely to be effective unless applied early in crop growth and if soil Olsen P is low (say <30 µg/mL).

Soil Olsen P (µg/mL)	Recommended P application (kg P/ha) to grow the crop	
	Scenario 1: Potential and field yield 150 t/ha	Scenario 2: Field yield 120 t/ha
20	280	190
30	180	90
35	130	20
40	70	nil
45	20	
50	nil	

Phosphorus and fruit quality

There is little conclusive evidence linking P supply with processing tomato quality. There is some suggestion that high applications of P may increase the proportions of unevenly ripened fruit (Winsor & Long 1967). Field experiments in New Zealand have not found such an effect.

Potassium (K)

Like potatoes, tomatoes take up large amounts of K. Unlike potatoes though, there is good evidence that tomato yield will often respond strongly to K fertiliser.

In Hawke's Bay and Poverty Bay, QT K is often very high by national standards. Nevertheless, tomatoes will often still respond to additional K applied, as long as it is incorporated well in advance of planting. This is because soils in Hawke's Bay and Poverty Bay tend to have high levels of exchangeable Ca and Mg, and these reduce the effectiveness of the soil K (Reid & Kale 1997; Reid et al. 2004).

Key point: Applying K fertiliser

K fertiliser is best applied as a base-dressing before raising beds. Side-dressed K will be ineffective.

For applications made a month or more ahead of planting use the cheapest source of K available (usually MOP). If applications must be made closer to planting, use SOP.

K applications should be broadcast and incorporated before planting to minimise the risk of plant osmotic stresses.

The result of this suppressive effect of soil Ca and Mg is that often in Hawke's Bay and Poverty Bay large applications of K fertiliser are needed for process tomatoes to approach their potential yields – much larger than usually applied overseas.

	Recommended K application (kg K/ha) to grow the crop	
Soil QT K	Scenario 1: Field yield 150 t/ha	Scenario 2: Field yield 120 t/ha
10	380	350
12	370	260
15	300	nil
16	250	
17	nil	

The above recommendations are calculated for a QT Ca of 18. If QT Ca<10 then there will be almost no yield response to K applied at QT K values greater than 13 (scenario 1) or 11 (scenario 2).

Potassium and fruit quality

Increases in QT K appear to decrease the percentage of reject fruit at harvest – but this benefit is lessened if QT Ca is high (Reid & Kale 1997). These benefits of a good soil K supply may be expressed through increased resistance to diseases, but further research is needed, because Reid and Kale (1997) found no evidence that K fertiliser applications affected fruit rejection rates.

Calcium (Ca), lime and soil pH

Applications of Ca to the soil are likely to decrease tomato yield and quality by suppressing K supply to the crop. There is evidence also that excessive Ca supply to the crop reduces tomato paste viscosity (Reid & Kale 1997).

Research carried out for Heinz Wattie's Ltd found that soil pH values as low as 5.0 did not appear to adversely affect yields in Hawke's Bay. Even if soil pH values are close to 5, the available evidence indicates that *lime should not be applied in the same growing season as tomatoes are grown*.

Key point: Ca, lime, and K supply

An experiment in 1998–99 compared two nearby sets of four plots on a silt loam soil in Hawke's Bay. All received the same fertiliser (13.5 kg P/ha, and 210 kg K/ha) but four plots were limed 30 days before planting and the rest were not. Compared with the non-limed plots, at planting time the limed plots had a higher pH (5.7 compared with 5.2), and slightly higher values for available N, Olsen P, and QT K. Despite this the average yield on the limed plots was only 90 t/ha compared with 107 t/ha on the non-limed plots.

Foliar applications of Ca compounds (at manufacturer's recommended rates) are unlikely to reduce yield and they may help reduce the incidence of blossom-end rot. In a limited number of field trials in Hawke's Bay, the effectiveness of such sprays varied between crops and seasons (Reid et al. 1994; Reid et al. 1993).

Sodium (Na)

There is no evidence that New Zealand soils contain insufficient Na for process tomato crops. Historically, growers have not applied Na except where it is a minor part of a compound fertiliser or trace element application, and for the present there is no recommendation to apply Na.

Usually tomatoes are regarded as sensitive to salinity stresses, which may be due chloride (Cl) as well as Na ions. In the glasshouse supplementing tomatoes with NaCl runs a risk of decreasing plant growth but it can benefit fruit production per plant and fruit quality (Satti et al. 1996; Satti & Lopez 1994). Part or all of this effect may be due to mild water stress of the plants rather than direct effects of Na itself.

Overseas, glasshouse tomato growers will often use intermittent treatments with NaCl to increase fruit soluble solids. In many crops Na may replace part (but not all) of the crops requirements for K provided that salinity stresses are minimised. Given the low cost of NaCl, and the large applications of K fertilisers often used for field tomatoes in New Zealand, there seems to be an opportunity for research to find safe effective ways of using NaCl in field tomato production.

Sulfur (S)

Yield or quality responses to fertiliser applications of S have not been observed in New Zealand. Soils used for process tomatoes in New Zealand usually contain large quantities of S already, and it is commonly applied in other fertilisers (e.g. superphosphate and potassium sulfate).

Trace elements

Experiments in Hawke's Bay indicate applications of trace elements are very unlikely to improve fruit yield or quality (Pearson & Reid 2000), but they may if there is strong evidence from previous crops that specific deficiencies have occurred. Maintenance applications are tiny, and availability of these nutrients is so dependent upon pH and changes soil water content (because of its effect on aeration) that trace element applications to the soil will usually be wasted.

A potential exception is that during water stress boron (B) supply from the soil may be inadequate for complete pollination, and may lead to blossom-end rot or internal blackening. Soil applications are unlikely to be effective, but some success has been achieved with foliar sprays of B plus Ca at manufacturer's recommended rates. It has proven difficult to achieve consistent control using those sprays, though (Reid et al. 1994; Reid et al. 1993), and with modern varieties the potential losses in crop value may be insufficient to justify the expense and effort of spraying.

Foliar nutrient sprays are best applied in the early morning or evening to extend the drying time and the opportunity for the nutrient to enter the leaves.

13.3. Maintenance nutrient applications

Table 13-1 shows the approximate amounts of nutrients that can be taken up by process tomato crops in New Zealand. Nutrients in the shoots but not the fruit are usually returned to the soil in crop residues.

Table 13-1. Typical amounts of major nutrients removed from the soil by an 83 t/ha tomato crop. These figures are based on the work of Sher (1996b) for a crop grown in Poverty Bay. Nutrients in the fruit are removed from the paddock, the rest are recycled.

	N	P	K	S	Ca	Mg
Shoots ex. fruit (kg/ha)	51	5	34	24	161	34
Fruit (kg/ha)	138	18	198	10	17	12
Total uptake (kg/ha)	189	23	232	34	178	46

Estimate maintenance requirements from the offtake in kg of each element per tonne of fruit removed from the field (Table 13-2). *Except under organic growing systems do not apply N fertiliser for maintenance* – see Chapter 2. For a crop yielding 120 t/ha in the field, and with 80% of the fruit sent to the factory, the maintenance P application would be about 0.22 x 120 x 80/100= 26 kg P/ha.

- Maintenance applications of any particular nutrient are recommended only if none is recommended to grow the crop.
- For N, maintenance applications should be considered only under organic production systems using composts.
- Methods for applying maintenance P and K should follow the guidelines for nutrients to grow the crop.
- Do not apply maintenance P if soil Olsen >55.
- Do not apply maintenance C if QT K>20.

Table 13-2. Typical maintenance nutrient requirements of process tomato crops. These values are calculated from the data in Table 13-1.

	N	P	K	S	Ca	Mg
kg/t fruit yield	1.7	0.2	2.4	0.1	0.2	0.1
Offtakes (kg/ha)						
Scenario 1: Field yield 150 t/ha	250	33	359	19	31	22
Scenario 1: Field yield 120 t/ha	200	26	287	15	25	17

Remember the values in the table are typical – nutrient concentrations can vary between crops.

13.4. Plant analysis

Typical nutrient concentrations in the youngest fully mature leaves, as quoted by testing laboratories, are of limited use as they often reflect considerable luxury uptake by the crops. The *critical nutrient concentration* below which plant growth is adversely affected is potentially more useful but the values will vary with plant size and the whole shoot must be measured. At present there are no values readily available, but Piggot (1986) quote deficient and adequate nutrient ranges for whole shoots that can be used instead (Table 6-3). To compare with these values, sample whole plants from 1 cm above ground when the plants have about 13 leaves. By that time it may be too late to affect the nutrition of that crop, but the results may be useful for managing future crops. The provenance of the data quoted by Piggot is poorly documented, and there is a need for measurements of critical, adequate and deficient nutrient concentrations through the whole life of tomato crops in New Zealand.

Table 13-3. Deficient and adequate nutrient concentrations for whole shoots of tomatoes (Piggot 1986). Values are given on a dry mass basis for plants with 13 leaves.

Nutrient		Deficient	Adequate
N	%	<3.0	4.0–6.0
P	%	<0.4	0.65–1.2
K	%	<3.0	4.0–6.0
Ca	%	<1.0	1.5–2.5
Mg	%	<0.3	0.4–0.4
B	µg/mL		40–100
Mn	µg/mL	<25	50–500
Zn	µg/mL	<20	30–200

Most likely deficiency symptoms

Nitrogen (N) deficiency is rarely observed in New Zealand. The symptoms are premature yellowing and death of the lower leaves.

Phosphorus (P) deficiency has become rare in the past 20 years. The symptoms may include stunted growth and very dark green leaves or in extreme cases even red colours on the leaves. It is risky to diagnose P deficiency on the basis of visual symptoms, though, as some tomato varieties have darker foliage than others, and red colours in the foliage are much more likely to result from cold stress.

Potassium (K) deficiency symptoms include chlorotic (whitened) areas on older leaves that eventually include small dry spots with brown margins. The leaf margins may become scorched and curls (resembling drought stress). The fruit ripen unevenly and may have a blotchy appearance.

Calcium deficiency in the whole plant is unknown in New Zealand, but localised Ca deficiency in some fruit is associated with blossom-end rot. It is induced mainly by water stress rather than insufficient Ca in the soil. Internal forms of blossom end-rot may reduce canning tomato quality and are hard to identify in the field. Although they are associated with decreased fruit concentrations of Ca they seem to be caused mainly by competition between roots and fruit for photosynthates during dry conditions (Reid et al. 1996).

Boron (B) deficiency may lead to poor fruit set. Deficiency is rarely sufficiently pronounced to cause visual symptoms in the leaves and stems.

Iron (Fe) deficiency is possible on alkaline soils but is rarely seen in New Zealand. The visual symptoms are pale green or white young leaves although the veins remain green.

14 Acknowledgements

To Plant & Food Research (Sustainable Agricultural Ecosystems Programme, funded by the Strategic Science Investment Fund) for supporting the writing and production of this report. To the Fertiliser Association of New Zealand, and the Vegetable Research and Innovation Board of Horticulture New Zealand Incorporated for part funding through preparation of the companion volume. The Vegetable Research & Innovation Board acknowledges the funding support of its member vegetable product groups: Vegetables NZ Inc, Process Vegetables NZ, Tomatoes NZ Inc, Onions NZ Inc, and the NZ Buttercup Squash Council.

To Horticulture New Zealand, Fertiliser Association of New Zealand, Heinz Wattie's Ltd, Ravensdown Fertiliser Ltd, Ballance Agrinutrients, Woodhaven Gardens Ltd, the Sustainable Farming Fund, Juice Products Ltd and Tim Addis for allowing us to use data that were either owned by them or originally gathered in projects carried out for them.

To Stephen Trolove for helpful suggestions throughout.

To Isabelle Sorensen, Yong Tan, Nathan Arnold, Brian Rogers, Jacinda English, Scott Shaw, Diana Mathers, Alan Kale, Carole Wright, Richard Gillespie, Sarah Sinton, and so many casual staff over the years, who helped with the experiments that made this book possible.

To the many growers who over the years have allowed access to their crops.

To David Sher for sharing his meticulous measurements of crop nutrient uptake.

To Duncan Greenwood and Colin Katz, both sadly deceased, for the inspiration to make sense of fertiliser experiments using models.

And to Di for supporting the intensity that inspiration demanded.

15 References

Abraham E, Cavanagh J-A, Wood P, Pearson A, Mladenov P 2016. Cadmium in New Zealand's agriculture and food systems. In: Singh LCaR ed. Integrated nutrient and water management for sustainable farming. Occasional report 29 Fertiliser and Lime Research Centre, Massey University. Palmerston North. Pp. 13.

Aitken AG, Hewett EW 2016. Fresh Facts. Auckland, New Zealand, The New Zealand Institute for Plant & Food Research Ltd. 37pp.

Allison MF, Fowler JH, Allen EJ 2001a. Effects of soil- and foliar-applied phosphorus fertilizers on the potato (*Solanum tuberosum*) crop. The Journal of Agricultural Science 137(04): 379-395.

Allison MF, Fowler JH, Allen EJ 2001b. Responses of potato (*Solanum tuberosum*) to potassium fertilizers. Journal of Agricultural Science Cambridge 136: 407-426.

Anon 2014. Code of Practice for Nutrient Management. Horticulture New Zealand. http://www.hortnz.co.nz/assets/Uploads/Code-of-Practice-for-Nutrient-Management-v-1-0-29-Aug-2014.pdf accessed 15-Oct-2018

Aslam T 2005. Investigations on growth and P uptake characteristics of maize and sweet corn as influenced by soil P status., Palmerston North, Massey University.

Basham CW, Ells JE 2015. Cucumbers, pumpkins, squash and melons. University of Colorado Extension. https://mountainscholar.org/bitstream/handle/10217/182386/AEXT_076092014.pdf?sequence=21 accessed 10 September 2018

Bishop P, Manning M 2011. Urea volatilisation: the risk management and mitigation strategies. In: Currie LD, Christenson CL eds. Adding to the knowledge base for the nutrient manager. Occasional Report No. 24. Fertiliser and Lime Research Centre. Palmerston North, Massey University. Pp. 1-13.

Burgmans JL, Watt JPC, Bussell WT 1998. Lessons from processing tomato irrigation trials in Hawke's Bay, New Zealand. New Zealand Journal of Crop and Horticultural Science 26: 307-312.

Buwalda JG 1986. Hybrid squash: yield responses to potassium and phosphorus fertilisers at four sites of varying initial fertility. New Zealand Journal of Experimental Agriculture 14: 347-354.

Buwalda JG 1987. The control of growth of hybrid squash (*Cucurbita maxima* L. cv Delica) by nitrogen. Journal of Plant Nutrition 10: 1843-1851.

Buwalda JG, Freeman RE 1986. Hybrid squash: responses to nitrogen, potassium, and phosphorus fertilisers on a soil of moderate fertility. New Zealand Journal of Experimental Agriculture 14: 339-345.

Buwalda JG, Rajan SSS, Scheffer JJC 1987. Reducing fertilizer requirements for hybrid squash (*Cucurbita maxima* L.) with localized applications of phosphorus and potassium and use of partially acidulated phosphate rock. Nutrient Cycling in Agroecosystems 13(2): 169-180.

Cantliffe DJ 1973. Nitrate accumulation in table beets and spinach as affected by nitrogen, phosphorus, and potassium nutrition and light intensity. Agronomy Journal 65(4): 563-565.

Carter KE, Stoker R 1988. Responses of non-irrigated and irrigated garden peas to phosphorus and potassium on Lismore stony silt loam. New Zealand Journal of Experimental Agriculture 16(1): 11-15.

Cavanagh J-A, Munir K, Gray C, Wakelin S, Chioma O, Jeyakumar J, Anderson C, Al Mamun S, Robinson B 2016. Assessing the significance of cadmium in New Zealand's agricultural systems - preliminary results. In: Singh LCaR ed. Integrated nutrient and water management for sustainable farming. Occasional report 29 Fertiliser and Lime Research Centre, Massey University. Palmerston North. Pp. 11.

Cavanagh J-A, Yi Z, Gray C, Young S, Smith S, Jeyakumar P, Munir K, Wakelin S, Lehoto NJ, Robinson B, Andrerson C 2018. Assessing cadmium uptake in New Zealand agricultural systems. In: Singh LCaR ed. Farm environmental planning - Science policy and practice. Occasional report 31 Fertiliser and Lime Research Centre, Massey University. Palmerston North. Pp. 12.

Ceesay MA 1980. Growth and nitrogen nutrition studies of onions (*Allium cepa* L.), Massey University, NZ.

Cooke GW 1982. Fertilizing for maximum yield. Third ed. St Albans, England, Granada. 465pp.

Cornforth IS, Sinclair TR 1984. Fertilizer recommendations for pastures and crops in New Zealand. Wellington, New Zealand Ministry of Agriculture and Fisheries. 76pp.

Craighead M, Martin R 2003. Fertiliser responses in potatoes–an overview of past Ravensdown research. Proceedings Agronomy Society of New Zealand 32: 15-25.

Craighead MD 2005. The effect of two lime sources on short-term changes in soil pH under Marlborough hill country pasture. Proceedings of the New Zealand Grassland Association 67: 155-162.

Curtin D, Beare MH, Lehto K, Tregurtha C, Qiu W, Tregurtha R, Peterson M 2017. Rapid assays to predict nitrogen mineralization capacity of agricultural soils. Soil Science Society of America Journal 81(4): 979-991.

Defra 2010. Fertiliser manual (RB209) 8th Edition. London, UK: Department for Environment, Food and Rural Affairs. Norwich, England, The Stationery Office Pp. 257.

Delahaut K, Newenhouse AC 1997. Growing pumpkins and other vine crops in Wisconsin. University of Wisconsin-Extension. http://learningstore.uwex.edu/assets/pdfs/A3688.PDF accessed 10 September 2018

Díaz-Pérez JC, Purvis AC, Paulk JT 2003. Bolting, yield, and bulb decay of sweet onion as affected by nitrogen fertilization. Journal of the American Society for Horticultural Science 128(1): 144-149.

Donald C, Porter I 2009. Integrated control of clubroot. Journal of Plant Growth Regulation 28: 289-303.

During C 1984. Fertilisers and soils in New Zealand farming. Wellington, Government Printing Office. pp.

Edmeades D, Metherell A, Waller J, Roberts A, Morton J 2006. Defining the relationships between pasture production and soil P and the development of a dynamic P model for New Zealand pastures: a review of recent developments. New Zealand Journal of Agricultural Research 49(2): 207-222.

Eko360 2014. Smartfert® in vegetables. Eko360 Limited. https://www.smartfert.co.nz/vegetables accessed 15-Oct-2018

El-Tarabily KA, Hardy GESJ, Sivasithamparam K, McKay AG 1997. Amendment of soil with lime or gypsum and its effect on cavity spot disease of carrots (*Daucus carota* L.) caused by *Pythium coloratum*. Australian Journal of Experimental Agriculture 37(2): 265-270.

Engel E, Baty C, le Corre D, Souchon I, Martin N 2002. Flavor-active compounds potentially implicated in cooked cauliflower acceptance. Journal of Agricultural and Food Chemistry 50(22): 6459-6467.

Everaarts A 1994. Nitrogen fertilization and head rot in broccoli. NJAS wageningen journal of life sciences 42(3): 195-201.

FANZ 2013. Code of Practice for Nutrient Management With Emphasis on Fertiliser Use. Fertiliser Association of New Zealand. http://www.fertiliser.org.nz/Site/code_of_practice/default.aspx accessed 20-May-2018

FAR 2012a. Nitrate leaching. Foundation for Arable Research. https://www.far.org.nz/assets/files/uploads/Nitrogen_leaching.pdf accessed 9-Jul-2018

FAR 2012b. Volatilisation. Foundation for Arable Research. https://www.far.org.nz/assets/files/uploads/Volatilisation.pdf accessed 20-May-2018

Francis G, Trimmer L, Tregurtha C, Williams P, Butler R 2003. Winter nitrate leaching losses from three land uses in the Pukekohe area of New Zealand. New Zealand Journal of Agricultural Research 46(3): 215-224.
Francis GS, Curtin D 2002. Understanding and interpreting soil N tests. FAR Arable Extra No. 37. Foundation for Arable Research. https://www.far.org.nz/assets/files/uploads/Extra_37.pdf accessed 22 May 2018
Freeman GG, Mossadeghi N 1972. Influence of sulphate nutrition on flavour components of three cruciferous plants: Radish (Raphanus sativus), cabbage (Brassica oleracea capitata) and white mustard (Sinapis alba). Journal of the Science of Food and Agriculture 23(3): 387-402.
Freeman M, Robson M, Lilburne L, McCallum-Clark M, Cooke A, McNae D 2016. Using OVERSEER in regulation - technical resources and guidance for the appropriate and consistent use of OVERSEER by regional councils. Report prepared by Freeman Environmental Ltd for the OVERSEER Guidance Project Board. Christchurch New Zealand, 115 p.

Goh KM, Vityakon P 1983. Effects of fertilisers on vegetable production 1. Yield of spinach and beetroot as affected by rates and forms of nitrogenous fertilisers. New Zealand Journal of Agricultural Research 26(3): 349-356.
Goh KM, Vityakon P 1986. Effects of fertilisers on vegetable production 2. Effects of nitrogen fertilisers on nitrogen content and nitrate accumulation of spinach and beetroot. New Zealand Journal of Agricultural Research 29(3): 485-494.
Greenwood D, Rahn C, Draycott A, Vaidyanathan L, Paterson C 1996. Modelling and measurement of the effects of fertilizer-N and crop residue incorporation on N-dynamics in vegetable cropping. Soil Use and Management 12(1): 13-24.
Greenwood DJ, Barnes A, Liu K, Hunt J, Cleaver TJ, Loquens SMH 1980a. Relationships between the critical concentrations of nitrogen, phosphorus and potassium in 17 different vegetable crops and duration of growth. Journal of the Science of Food and Agriculture 31: 1343-1353.
Greenwood DJ, Cleaver TJ, Turner MK, Hunt J, Niendorf KB, Loquens SMH 1980b. Comparison of the effects of nitrogen fertilizer on the yield, nitrogen content and quality of 21 different vegetable and agricultural crops. Journal of Agricultural Science Cambridge 95: 471-485.
Greenwood DJ, Cleaver TJ, Turner MK, Hunt J, Niendorf KB, Loquens SMH 1980c. Comparison of the effects of phosphate fertiliser on the yield, potassium content and quality of 22 different vegetable and agricultural crops. Journal of Agricultural Science Cambridge 95: 457-469.
Greenwood DJ, Cleaver TJ, Turner MK, Hunt J, Niendorf KB, Loquens SMH 1980d. Comparison of the effects of potassium fertiliser on the yield, potassium content and quality of 22 different vegetable and agricultural crops. Journal of Agricultural Science Cambridge 95: 441-456.
Greenwood DJ, Stone DA 1998. Prediction and measurement of the decline in the critical-K, the maximum-K and total cation plant concentrations during the growth of field vegetable crops. Annals of Botany 82: 871-881.
Hanly JA, Gregg PEH 2004. Green-manure impacts on nitrogen availability to organic sweetcorn (Zea mays). New Zealand Journal of Crop and Horticultural Science 32(3): 295-307.
Hansen LN 2000. Dry matter and nitrogen partitioning in sweet corn (Zea mays L.) for processing : a thesis presented in partial fulfilment of the requirements for the degree of Doctor of Philosophy in Plant Science at Massey University. Doctoral thesis, Massey University.
Hansen M, Laustsen AM, Olsen CE, Poll L, Sørensen H 1997. Chemical and sensory quality of broccoli (Brassica oleracea L. Var Italica). Journal of Food Quality 20(5): 441-459.
Haynes RJ 1988. Soil requirements of blueberries in relation to their nutrition. Procedings of the Agronomy Society of New Zealand 18: 143-147.

Haynes RJ, Martin RJ, Goh KM 1993. Nitrogen fixation, accumulation of soil nitrogen and nitrogen balance for some field-grown legume crops. Field Crops Research 35(2): 85-92.
Hedley J, Close RC 1985. Tuber-borne diseases of potatoes. Potato growing: a changing scene. Lincoln Special Publication 3, Agronomy Society of New Zealand. Pp. 49-54.
Hewitt AE 2010. New Zealand soil classification. Third ed. Lincoln, New Zealand, Manaaki Whenua Press. 136pp.
Horneck D, Rosen C 2008. Measuring nutrient accumulation rates of potatoes - tools for better management. Better Crops 92(1): 4-6.
Hume E, Brown H, Sinton SM, Meenken ED 2015. Arable and horticultural crop modelling for the Matrix of Good Management - a technical summary Plant & Food Research report 12430, for Environment Canterbury., 168 p.
Hunt A, Finlayson C, Dellow S, Gillespie RN, Arnold N, Johnstone PR, Reid JB 2015. Building a brighter future for process carrots - Year 2 annual report. Havelock North, New Zealand Insitute for Plant and Food Research 30 p.
Hunt A, Johnstone PR, Dellow S, Gillespie RN, Sorensen IB, Liu J, Arnold N, Reid JB, Hedderley D 2016. Building a brighter future for process carrots - Year 3 annual report. Havelock North, New Zealand Insitute for Plant and Food Research. 30 p.
Hunt A, Reid JB, Johnstone PR 2017. Optimising sweet corn plant population by planting date combinations across New Zealand. Agronomy New Zealand 46: 49-57.
IPNI 2018. IPNI Estimates of Nutrient Uptake and Removal. International Plant Nutrition Institute. http://www.ipni.net/article/IPNI-3296 accessed 28 May 2018
Jamieson PD, Stone PJ, Zyskowski RF, Sinton SM, Martin RJ 2004. Implementation and testing of the Potato Calculator, a decision support system for nitrogen and irrigation management. In: MacKerron DKL, J. HA eds. Decision support systems in potato production: bringing models to practice. Wageningen; Netherlands, Wageningen Academic Publishers. Pp. 85-99.
Jamieson PD, Zyskowski RF, Li FY, Semenov MA 2008. Water and N uptake and responses in models of wheat, potatoes and maize. In: Ma L, Ahuja LR, Bruulsema TW eds. “Quantifying and Understanding Plant Nitrogen Uptake Systems Modeling”. Boca Raton, FL, CRC Press. Pp. 127-146.
Jamieson PD, Zyskowski RF, Sinton SM, Brown HE, Butler RC 2006. The Potato Calculator: a tool for scheduling nitrogen fertilizer applications. Agronomy New Zealand 36: 49-53.
Jenkins PD, Ali H 2000. Phosphate supply and progeny tuber numbers in potato crops. Annals of Applied Biology 136: 41-46.
Johnstone PR, Reid JB, Pethybridge S, Gillespie RN, Walson C, Dellow S, Sorensen IB, Gosden P, Searle BP, Bulman S 2014. Building a brighter future for process carrots - Year 1 annual report. Havelock North, New Zealand Insitute for Plant and Food Research 30 p.
Khaembah E, Brown H 2016. OVERSEER crop module testing – end of project report Plant & Food Research report 12430, for Foundation for Arable Research. 22 p.
King D, Wishart G 1990. Buttercup squash—cultural guidelines for export production. Wellington, New Zealand, New Zealand Buttercup Squash Council. pp.
Kirkman JH, Basker A, Surapaneni A, MacGregor AN 1994. Potassium in the soils of New Zealand—A review. New Zealand Journal of Agricultural Research 37(2): 207-227.
Kolota E, Czerniak K 2010. The effects of nitrogen fertilization on yield and nutritional value of swiss chard. Acta Scientiarum Polonorum. Hortorum Cultus 9(2): 31-37.
Kristensen HL, Thorup-Kristensen K 2007. Effects of vertical distribution of soil inorganic nitrogen on root growth and subsequent nitrogen uptake by field vegetable crops. Soil Use and Management 23(4): 338-347.

Kumar R 2015. Nutritional deficiencies/disorders of potato. http://vikaspedia.in/agriculture/crop-production/integrated-pest-managment/ipm-for-vegetables/ipm-strategies-for-potato/nutritional-deficiencies-disorders-of-potato#section-1 accessed 12 March 2018.

Lambert DH, Manzer FE 1991. Re;ationship of calcium to potato scab. Phytopathology 81: 632-636.

Lester GE, Grusak MA 2004. Field application of chelated calcium: Postharvest effects on cantaloupe and honeydew fruit quality. HortTechnology 14(1): 29-38.

MacLaren RG, Cameron KC 1990. Soil science: an introduction to the properties and management of New Zealand soils. Oxford University Press.

Marschner H 1995. Mineral nutrition of higher plants. 2nd ed. London, Academic Press. 674pp.

McCallum J, Porter N, Searle B, Shaw M, Bettjeman B, McManus M 2005. Sulfur and nitrogen fertility affects flavour of field-grown onions. Plant and Soil 269(1): 151-158.

McLeod CC 1987. Use and misuse of fertilisers on peas. Peas: Management for Quality: Agronomy Society of New Zealand Special Publication No. 6, Agronomy Society of New Zealand. Pp. 29-31.

Motes J, Roberts W, Damicone J, Edelson J, Duthie G 2007. Squash and pumpkin production. Oklahoma Cooperative Extyension Service. http://dasnr22.dasnr.okstate.edu/docushare/dsweb/Get/Version-7493/HLA-6026web.pdf accessed 10 September 2018

Norris M, Hunt A, Dellow S, Arnold N, Liu J, Sorensen IB, Tan Y, Johnstone PR 2017. Nitrogen — Measure it and manage it: Year 1 summary report. Plant and Food Research Ltd client report 16170 to Foundation for Arable Research. Havelock North, New Zealand Insitute for Plant and Food Research 32 p.

Norris M, Hunt A, Dellow S, Arnold N, Liu J, Tan Y, Hedderley D 2018. Nitrogen — Measure it and manage it: Year 2 summary report. Plant and Food Research Ltd client report 16566 to Foundation for Arable Research. Havelock North, New Zealand Insitute for Plant and Food Research 24 p.

Nott H, Falloon R, Gowers S 1994. Clubroot. Crop & Food Research. http://www.freshvegetables.co.nz/assets/Members-pdfs/F001319250-1994-Clubroot-of-vegetable-brassicas-a-review-2.pdf accessed 11 September 2018

Paredes C, Cegarra J, Bernal MP, Roig A 2005. Influence of olive mill wastewater in composting and impact of the compost on a Swiss chard crop and soil properties. Environment International 31(2): 305-312.

Pearson AJ, Reid JB 2000. Process tomato responses to micronutrients and magnesium. NZ Institute for Crop & Food Research Ltd report to Heinz Wattie's Australasia Ltd, Crop & Food Confidential Report No. 232. 16 p.

Pearson AJ, Reid JB, Watt R 2004. Optimising fertiliser for profitable carrot production. Final report on AgMardt grant number 20121. Hastings, NZ Institute for Crop and Food Research.

Pearson AJ, Renquist AR, Reid JB 1999. MAF vegetable fertiliser trials - a reappraisal using a new model. CropInfo Confidential Report 590. Lincoln, NZ, Crop & Food Research. 37 p.

PIDG 2008. Making peas pay. Lincoln, NZ, Pea Industry Development Group, Foundation for Arable Agriculture. 66pp.

Piggot TJ 1986. Vegetable crops. In: Reuter DJ, Robinson JB eds. Plant analysis: an interpretation manual. Melbourne, Inkata Press. Pp. 148-187.

Pokluda R, Kuben J 2002. Comparison of selected Swiss chard (Beta vulgaris ssp. cicla L.) varieties. Horticultural Science 29: 114-118.

Prasad M, Spiers TM, Ravenwood IC 1988. Target phosphorus soil test values for vegetables. New Zealand Journal of Experimental Agriculture 16: 83-90.

Randle WM, Kopsell DE, Kopsell DA 2002. Sequentially reducing sulfate fertility during onion growth and development affects bulb flavor at harvest. HortScience 37(1): 118-121.

Reid JB 2002. Yield response to nutrient supply across a wide range of conditions. 1. Model derivation. Field Crops Research 77: 161-171.

Reid JB 2016a. A preliminary model of sweet corn growth and yield. New Zealand Journal of Crop and Horticultural Science 45(2): 130-149.

Reid JB ed 2016b. The Sweet Corn Toolkit Manual 2nd Edition. Second ed. Wellington, Process Vegetables New Zealand.

Reid JB, English JM 2000. Potential yield in carrots: theory, test and an application. Annals of Botany 85: 593-605.

Reid JB, Gillespie RN 2017. Yield and quality responses of carrots (*Daucus carota* L.) to water deficits. New Zealand Journal of Crop and Horticultural Science 45(4): 299-312.

Reid JB, Hunt AG, Johnstone PR, Searle BP, Jesson LK 2017. On the responses of carrots (*Daucus carota* L.) to nitrogen supply. New Zealand Journal of Crop and Horticultural Science. 2017 ed. Pp. 1-21.

Reid JB, Kale AJ 1997. Process tomato quality as affected by soil fertility and water deficit. In: Currie LD, Loganathan P eds. Nutritional requirements of horticultural crops. Occasional report No. 10. Fertilizer and Lime Research Centre. Palmerston North, Massey University. Pp. 52-60.

Reid JB, Morton JD 2018. Nutrient recommendations for vegetable crops in NZ. 1st ed. Wellington, New Zealand, Horticulture New Zealand Inc. ISBN 978-0-473-46745-6. 133pp.

Reid JB, Pearson AJ, English JM 2000a. Land management for process tomatoes. Recommended best management practices for New Zealand. Lincoln , New Zealand. 41 p.

Reid JB, Pearson AJ, Kale AJ 2004. The Tomato Calculator - a case study of developing decision support software for New Zealand's process tomato growers. Acta Horticulturae 694: 237-241.

Reid JB, Pearson AJ, Stone PJ 2000b. Sustainable soil management for profitable crop production. Proceeding NZ Fertiliser Manufacturers Research Association 26th Technical Conference, Lincoln, November 2000. Pp. pp129-141.

Reid JB, Pearson AJ, Stone PJ 2001. Sustainable Crop Production SMF Contract 2120. Crop & Food Research Confidential Report No. 341 to Ministry for the Environment, Heinz-Watties Australasia Ltd, Foundation for Arable Research, NZ Vegetable and Potato Growers Federation, NZ Fertiliser Manufacturers Research Association. Hastings, New Zealand. 17 p.

Reid JB, Searle BP, Pearson AJ 2002a. Lettuce and fertilisers. Hastings, New Zealand Institute for Crop & Food Research confidential report 561. 18 p.

Reid JB, Searle BP, Pearson AJ 2002b. Lettuce and fertilisers. New Zealand Institute for Crop & Food Research confidential report 561. Hastings, Crop & Food Research. 18 p.

Reid JB, Searle BP, Sinton SM 2011. Does my potato crop need fertiliser? A modeling approach. Agronomy New Zealand 41: 79-95.

Reid JB, Searle BP, Sinton SM, Michel A, Meenken ED, Brown H, Roberts A, Manning M 2016a. Fertiliser practice and yield losses in process potato crops grown in Canterbury, New Zealand. New Zealand Journal of Crop and Horticultural Science 44(1): 41-57.

Reid JB, Stone PJ, Pearson AJ, Wilson DR 2002c. Yield response to nutrient supply across a wide range of conditions. 2. Analysis of maize yields. Field Crops Research 77: 173-189.

Reid JB, Viljanen-Rollinson S, Fletcher J, James T 2016b. Identifying production constraints in processing beans. Havelock North, New Zealand Insitute for Plant and Food Research 4p.

Reid JB, Winfield DJ, Sorensen IB 1994. Effects of irrigation and foliar sprays on tomato fruit quality. CropSeed Confidential Report 131 New Zealand Institute for Crop & Food Research Ltd, Lincoln, New Zealand. 25 p.

Reid JB, Winfield DJ, Sorenson IB 1993. Internal blackening of tomatoes. CropSeed Confidential Report 61 NZ Institute for Crop & Food Research Ltd report to J.Watties Foods Ltd. 25 p.

Reid JB, Winfield DJ, Sorenson IB, Kale AJ 1996. Water deficit, root demography, and the causes of internal blackening in field-grown tomatoes (*Lycopersicon esculentum* Mill.). Annals of Applied Biology 129: 137-149.

Renquist AR, Pearson AJ, Reid JB 1998. MAF vegetable fertiliser trials - a reappraisal using a new model. Crop & Food Research CropInfo Report 590 New Zealand Institute for Crop & Food Research. 37 p.

Riley H, Vågen I 2003. Critical N-concentrations in broccoli and cauliflower, evaluated in field trials with varying levels and timing N fertilizer. International Society for Horticultural Science (ISHS), Leuven, Belgium. Pp. 241-249.

Roberts A, Morton J 2016. Fertiliser use on New Zealand dairy farms, New Zealand Fertiliser Manufacturers' Association, Auckland, New Zealand. 52pp.

Santamaria P, Elia A, Serio F, Todaro E 1999. A survey of nitrate and oxalate content in fresh vegetables. Journal of the Science of Food and Agriculture 79(13): 1882-1888.

Satti SME, Al-Yhyai RA, Al-Said F 1996. Fruit quality and partitioning of mineral elements in processing tomato in response to saline nutrients. Journal of Plant Nutrition 19(5): 705-715.

Satti SME, Lopez M 1994. Effect of increasing potassium levels for alleviating sodium chloride stress on the growth and yield of tomato. Communications in Soil Science and Plant Analysis 25(15-16): 2807-2823.

Scaife A, Turner M 1983. Diagnosis of Mineral Disorders in Plants Volume 2. Vegetables. London, HMSO. 96pp.

Searle BP, Reid JB 2004. Predicting fertiliser requirements of lettuce. Hastings, New Zealand Institute for Crop & Food Research confidential report 1249. 18 p.

Searle BP, Renquist AR, White M 2006. Reducing and predicting squash storage rots. Report to Sustainable Farming Fund, June 2006. Hastings., New Zealand Institute for Crop & Food Research 23 p.

Sher DJ 1996a. Fertiliser for onions. The Grower(February 1996): 10-13.

Sher DJ 1996b. Nutrient uptake of vegetable crops. Summary of results 1993-96. Confidential report to BASF and Ravensdown Fertiliser Ltd., 26 p.

Sher DJ 1997. Growth and nutrient absorption of a Manawatu potato crop from planting to maturity. In: Currie LD, Loganathan P eds. Nutritional requirements of horticultural crops. Occasional report No. 10. Fertilizer and lime research centre. Palmerston North, Massey University. Pp. 29-35.

Sorensen J 1999. Nitrogen effects on vegetable crop production and chemical composition. Acta Horticulturae 506: 41-50.

Syed N, Munir M, Alizai AA, Ghafoor A 2000. Onion yield and yield components as function of the levels of nitrogen and potassium application. Pakistan Journal of Biological Sciences 3(12): 2069-2071.

Tekalign T, Abdissa Y, Pant LM 2012. Growth, bulb yield and quality of onion (Allium cepa L.) as influenced by nitrogen and phosphorus fertilization on vertisol. II: Bulb quality and storability. African Journal of Agricultural Sciences 7: 5980 -5985.

Thomson B, Nokes C, Cressey P 2007. Intake and risk assessment of nitrate and nitrite from New Zealand foods and drinking water. Food Additives and Contaminants 24(2): 113-121.

Tregurtha CS, Wilson DR, Williams PH, Reid JB 1998. Fertiliser requirement for process beans. Commercial Grower 53: 35.

USDA 2018. Nutrient Content of Crops. United States Department of Agriculture, Natural Resources Conservation Service. https://plants.usda.gov/npk/main accessed 5 June 2018

Wallace EGR 2000. VGH 2000 Vegetable Growers Handbook, Agro-Research Publishing, NZ. 223pp.

Watkins N, Selby D 2015. Techhnical description of OVERSEER for Regional Councils. Report Prepared for Bay of Plenty Regional Council RE500/2015/084. AgResearch AgResearch, New Zealand. 37 p.

Webster AB 1969. Manuring and spacing experiments on vegetables. New Zealand Journal of Agricultural Research 12: 381-416.

Williams PH, Tregurtha RJ, Francis GS 2003. Fate of urea applied to winter spinach in New Zealand. Nutrient Cycling in Agroecosystems 67(3): 245-254.

Willis G 2018. Using Overseer in Water Management Planning. An overview guideline. Report for Overseer Ltd. Pukekohe, Enfocus Limited, 36B Jellicoe Road, Pukekohe. 26 p.

Wilson DR 1987. New approaches to understanding the growth and yield of pea crops. Peas: Management for Quality: Agronomy Society of New Zealand Special Publication No. 6, Agronomy Society of New Zealand. Pp. 23-28.

Wilson DR, Martin RJ, Rea MB, Reid JB 2000. Forecasting potential yield and fertiliser requirements of process beans. Crop & Food Research Confidential Report 201, for NZ Vegetable and Potato Growers Federation., 12 p.

Wilson DR, Tregurtha CS, Williams PH, Curtin D 1999. Yield response of field and process peas to fertiliser application. Agronomy New Zealand 29: 17-22.

Wilson DR, Tregurtha CS, Williams PH, Reid JB 1998. Yield response of process beans to fertiliser application Crop & Food Research Confidential Report 490, for NZ Vegetable and Potato Growers Federation., 5 p.

Wilson GJ, Scheffer JJC 1983. Potassium responses in onions and spinach (summary). Commercial Grower 38(11): 16.

Winsor, G.W., Long MIE 1967. The effects of nitrogen, phosphorus, potassium, magnesium and lime in factorial combination on ripening disorders of glasshouse tomatoes. Journal of Horticultural Science 42: 391-402.

Wood RJ 1997. Fertiliser use for vegetable crop production. In: Currie LD, Loganathan P eds. Nutritional requirements of horticultural crops. Occasional report No. 10. Fertilizer and lime research centre. Palmerston North, Massey University. Pp. 21-27.

Wood RJ, Cornforth IS, Douglas JA, Malden GE, Prasad M, Wilson GJ 1986. Vegetables. In: Clark CJ, Smith GS, Prasad M, Cornforth IS eds. Fertiliser recommendations for horticultural crops grown in New Zealand. Wellington, New Zealand Ministry of Agriculture and Fisheries. Pp. 57-69.

Wright PJ 1993. Effects of nitrogen fertiliser, plant maturity at lifting, and water during field-curing on the incidence of bacterial soft rot of onions in store. New Zealand Journal of Crop and Horticultural Science 21(4): 377-381.

Yara 2017. Yara CheckIT. An agriculture mobile app that gives farmers a photographic library of crops to allow a simple and fast identification of possible nutrient deficiencies.

Zaman M, Saggar S, Stafford A 2013. Mitigation of ammonia losses from urea applied to a pastoral system: The effect of nBTPT and timing and amount of irrigation. Proceedings of the New Zealand Grassland Association 75: 209-214.

Zhang W, Chen X-X, Liu Y-M, Liu D-Y, Chen X-P, Zou C-Q 2017. Zinc uptake by roots and accumulation in maize plants as affected by phosphorus application and arbuscular mycorrhizal colonization. Plant and Soil 413(1): 59-71.

DISCOVER. INNOVATE. GROW.