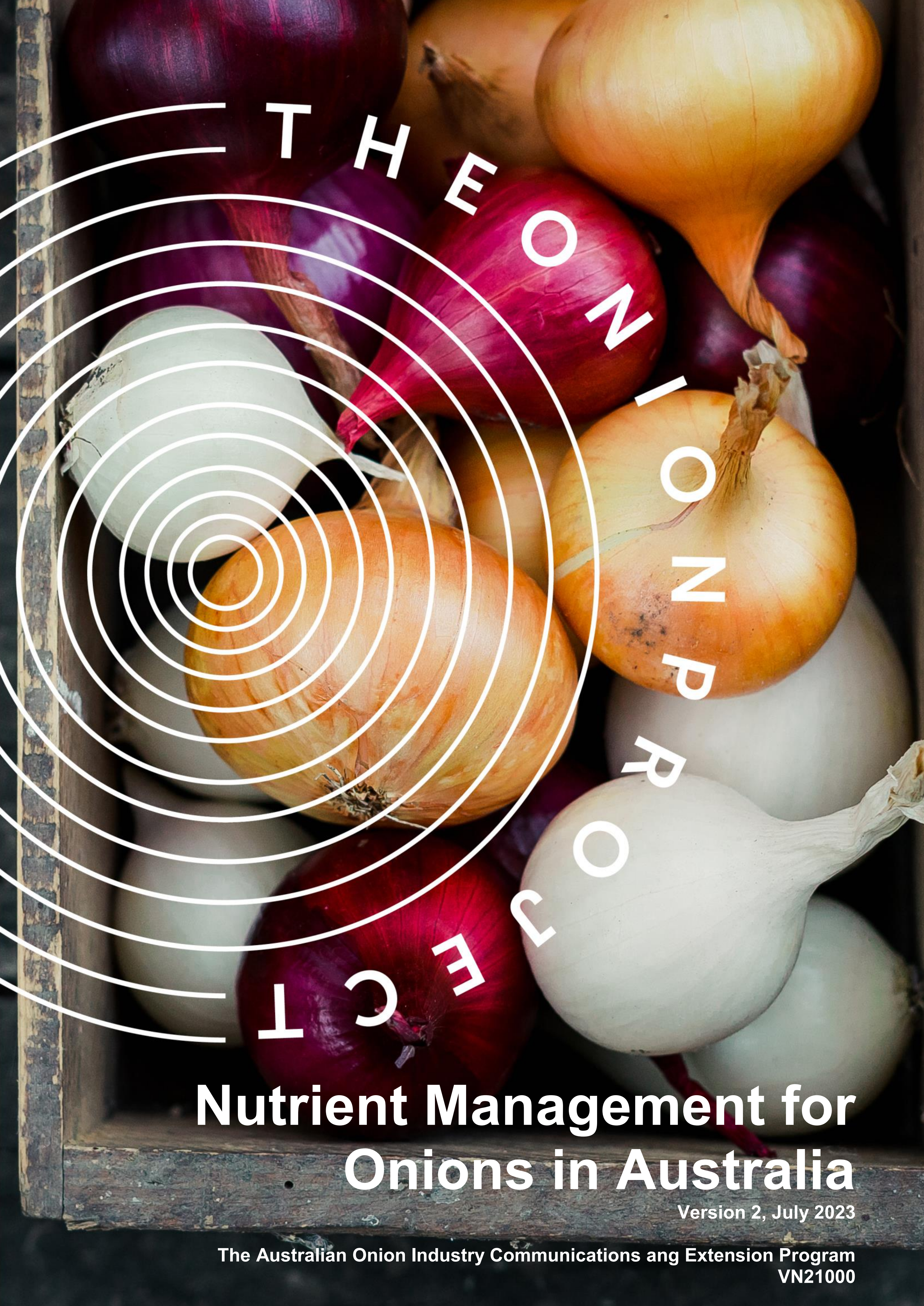

Nutrient Management for Onions in Australia

Version 2, July 2023

The Australian Onion Industry Communications ang Extension Program
VN21000

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This guide

This guide provides information for good nutrient management of Australian onion crops.

This nutrient management guide is designed for onion growers and crop advisors who aim to produce high-quality crops without wasting nutrients. It covers:

- An overview of onion growth and nutrient needs
- Information on onion root growth and development
- An overview of nutrient needs of onion crops
- An approach to nutrient budgeting, determining nutrient needs and nutrition strategies for onions
- An overview of key soil factors affecting nutrient availability and uptake, especially pH
- Information on key nutrients and use for onion crops
- An introduction to crop nutrition monitoring
- Information on how nutrients get from the soil into the plant and nutrient interactions
- Information on fertiliser nutrient composition and concentration
- Information on nutrient stewardship.

Key points

- The nutrient requirements of onion crops largely depend on a range of factors, such as variety, plant density, production environment, pest and disease pressure, soil fertility, approach to fertiliser and soil amendment use, and irrigation management.
- Nutrient budgets have to take the amount of plant-available mineral nutrients in the topsoil into account and consider that onions may acquire nutrients mainly from the top 30 cm of soil but can explore up to 60 cm soil depth, if there are no rootzone restrictions, e.g., pH change, compaction, water logging.
- Published research data on onion nutrition and nutrient removal suggests that, on average, 120 to 140 kg nitrogen (N), 22–26 kg phosphorous (P) and 150 kg potassium (K) per hectare would have to be available for uptake from soil reserves, soil amendments and fertilisers together. Given P dynamics in different soils, P inputs commonly must be applied at several times that of the removal rate.
- As an example, 60 tonnes of onion bulbs harvested per hectare may remove more than 100 kg/ha of nitrogen (N), around 20 kg/ha of phosphorus (P) and 120 kg/ha of potassium (K).
- Much of the research into onion nutrition dealt with single elements – e.g., N, P, K, S or Ca – or is focused on a limited group of nutrients such as N:P:K or trace metals.
- There is limited independent research available on the use of soil amendments that are available in Australia, and trials are commonly run with ‘traditional’ fertilisers such as urea, DAP, MAP or muriate of potash and sulphate forms of trace elements.
- Many ‘fertiliser recipes’ are based on regional experiences, and thus on certain soil, climate and crop rotation conditions. Most publications fail to describe all or some of these conditions, even omitting the variety used and yield level. Therefore, ‘recipes’ should be used with caution, as a guide only.

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The best approach to managing onion nutrition is to develop a site-specific nutrient budget based on:

- Soil testing data, yield targets and crop removal rates
- Split nitrogen applications according to needs at different growth stages
- Monitoring of nutrient uptake via plant testing, so that adjustments can be made with topdressing rates and/or with foliar application of additional nutrients or fertigation
- A good understanding of the function and the pros and cons of different fertiliser products and application methods, as well as knowledge of the impact of soil amendments
- Regional experience that is based on a good understating of onion nutrition management.

Acknowledgement of Country

We acknowledge the Traditional Owners of the Country that we work on throughout Australia and recognise their continuing connection to land, waters and culture. We pay our respects to their Elders past, present and emerging and the Elders of other Aboriginal and Torres Strait Islander communities. Moreover, we express gratitude for the knowledge and insight that Traditional Owner and other Aboriginal and Torres Strait Islander people contribute to our shared work.

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1 Onion growth and nutrient needs

Knowing how onion plants grow is important for developing an effective nutrient management program. Table 1 provides and overview of growth stages and general requirements at each stage.

Table 1: Onion growth stages and nutrition focus

CROP STAGE	IMAGE	DESCRIPTION	COMMENTS	FOCUS
Preplant		Final planning for the onion crop well ahead of seeding	Onions require a firm, fine seedbed and friable soil structure (no compaction). The potential rooting depth is 75 cm; 75% of after and nutrient are taken up from the top 30 cm of topsoil. Organic matter improves soil condition, air and water volumes and nutrient holding capacity for onions.	Soil (nutrients, diseases), water testing, preplant and in season nutrient budgeting/planning based on test results. Seed testing for germination % and disease. Soil preparation, (after timely termination of cover crops, if used) pre-plant fertiliser application, addition of soil amendments (if used).
Planting		Seeding	Nitrogen is easily lost via leaching or denitrification in wet soils. Therefore, applications at planting should only cater for the time until first topdressing. Soil reserves should be considered when determining N-applications.	Ensure there is adequate phosphorus (P) and some nitrogen (N) applied as a broadcast, banded or fertigation, if feasible.
Germination / emergence		Radicle and flag leaf emergence	Onions can germinate at low temperatures, but $>10^{o}C$ is best for uniform crops.	Irrigation to ensure even germination while ensuring that the soil is never waterlogged. Phosphorus (P) and calcium (Ca) must be available to the young roots from the soil solution. Liquid products may be suitable to ensure there is enough soluble P and Ca in the soil solution.
Establishment		1-2 true leaves developed	Slow growth to the 3-leaf stage.	Very low nutrient needs, herbicide damage, low soil temperatures or soil acidity can slow growth down further. Note that this can look like nutrient deficiency, but it should not be ‘fixed’ via applying fertilisers.

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CROP STAGE	IMAGE	DESCRIPTION	COMMENTS	FOCUS
Leaf (vegetative) growth		3-4 true leaves developed	Leaf growth rate increases with temperature. Maximum leaf growth rate is at around 27°C. Onion root growth from the basal plate matches leaf growth.	Seedling vigour plays a crucial role in the development and quality of bulbs, whose size depends on the number and expansion of green leaves at bulb development. It is therefore important to not set crops back during that time, including via herbicides.
Early bulb initiation		4-7 true leaves (leek stage); from the 4th leaf onwards, the neck just starts to thicken	Most onion varieties initiate bulbs after the 6-8 leaf stage. Bulb initiation occurs in response to increasing day length. Major onion types differ in the minimum day length needed to initiate bulbing. The leaf bases (called a 'bulb scale' in botanical terminology) form the onion bulb 'rings.' The minimum day length needed for bulbing is much shorter for early, overwintering onions, than for spring seeded varieties. Temperature and light spectral quality also affect the onset of bulbing, to a lesser degree compared to day length. Once day length initiates bulbing, the higher the temperature, the earlier bulbing will occur. Densely planted onions have more shaded leaves and begin bulbing earlier because of altered light spectral quality.	It is important that all nutrients are available and in balance. It is worth checking this via sap testing early during this stage. Apart from nitrogen, additional nutrients may be required such as phosphorus (P) and potassium (K). Both can either be side dressed or applied to foliage (e.g., together with a compatible fungicide). Trace elements can be applied to foliage.
Bulbing		8-12 true leaves, bulbs develop to around twice the size of the neck; the plant reaches close to maximum height; the growth stage is called bulbing when the bulb diameter reaches twice that of the neck		A period of rapid nutrient uptake starts with bulbing. Well growing onions crops may take up around 100 kg per hectare of nitrogen, potassium, and calcium by this stage, and substantially smaller amounts of sulphur, phosphorus, and magnesium during that time. From initial bulbing to harvest, nutrient uptake into leaf tissue decreases, while nutrient uptakes into onion bulbs increases substantially. No more nitrogen should be applied to soils after bulbing. While nitrogen is still taken up, the rate of N uptake drops consistently between bulbing and maturing.
Bulb development / growth		Leaf number and leaf area stays the same. Leaves elongate and bulb grows in diameter	In a good crop, dry matter accumulates at a rate of 100 to 200 kg per hectare per day during the peak growth period.	The onion plant has the highest demand for water and nutrients during bulb growth. Calcium is critical at bulb development for cell structure and improve shelf life. Ideally, all required nutrients are available from the soil at this stage to support bulb growth.

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CROP STAGE	IMAGE	DESCRIPTION	COMMENTS	FOCUS
Maturing		Bulb enlargement moves towards completion; by end of the stage more than 50% of tops are down	Sparse, uneven crops; late planting; and nutrient excess, deficiencies or imbalances can all negatively affect crop development, maturity, and quality. Hail damage and/or excessively cool or hot growing conditions can affect maturing and reduce quality and storability. Wet weather during field curing increases the risk of storage losses.	During mid-late stages of development, potassium demand is at its highest and can be applied in the form of potassium nitrate or as a thiosulphate. Crops that have been oversupplied with nitrogen will generally mature more slowly and have thick necks that dry slowly. They may be more prone to skinning, and to post-harvest diseases and disorders. In Europe, growers test for available soil nitrogen after lifting/harvest to assess storage risks. If the remaining nitrogen (as nitrate N plus ammonium N) is above 50 kg N per hectare, the crop is considered a high-risk, as it may not store or travel well. It therefore needs to be marketed as soon as possible.
Harvest (or lifting and field curing in some production systems)		Tops dry off		

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Root growth and development

Roots are the main organs of nutrient uptake. Nutrient uptake is directly correlated to root length and density, i.e., how much soil volume the root system can explore. Topsoil depth and soil structure are important factors that influence root growth potential. Organic matter helps with nutrient holding and cycling, and it protects nutrients from leaching.

Onions have a shallow, sparsely branched root system, with most roots in the top 30 cm of soil. Rooting density decreases with soil depth. The sparse, unbranched, and shallow onion root system means that the root/soil interface is smaller than that of crops with highly branched, fibrous and/or deep root systems. This leads to:

- Low uptake efficiency of relatively immobile nutrients (phosphorus (P); potassium (K); and some micronutrients such as zinc (Zn); therefore, onions are more susceptible than most crops to deficiencies of these nutrients.
- Potential losses of mobile nutrients from the root zone due to rain or overirrigation, especially on light soils and when soil moisture levels are high; mobile nutrients include nitrogen (N), sulphur (S), and boron (B); potassium (K) losses can also occur on light soils.

Onions are highly dependent on vesicular-arbuscular mycorrhizal (VAM) fungi for the uptake of phosphorus from soils with low to medium P concentrations (identified by soil tests). These Mycorrhizal fungi produce a network of threadlike hyphae that extend from the onion roots into the soil, greatly increasing the absorptive surface area of the roots. Mycorrhizal fungi also can increase the uptake of zinc and other micronutrients in some high pH, calcareous soils. Mycorrhizal fungi usually are abundant in agricultural soils, except when nonhost crops (e.g., brassicas) are grown, soil is fumigated, or soil test P is high. In research trials, the mycorrhizal infected plants showed improved development and a significantly improved ability to uptake nutrients and water, as well increased resistance to stresses (e.g., diseases).

Appendix 2 explains how nutrients get from the soil into plants; Appendix 3 provides information on nutrient interactions that may influence uptake.

Further information on mycorrhiza fungi for growers: https://www.soilwealth.com.au/resources/articles-and-publications/using-mycorrhizae-to-boost-vegetable-crop-quality-and-yield/

Nematode feeding and root diseases can cause weak, poorly developed root systems.

Further information for growers:

- https://www.soilwealth.com.au/resources/article-publication/management-of-rootknot-nematode-in-vegetable-crops/
- https://www.soilwealth.com.au/resources/webinar-recordings/nematodes-in-vegetable-soils-managing-the-bad-and-good-ones-with-dr-sarah-collins/

Compaction and other subsoil constraints can restrict root growth.

Onions are sensitive to moderately sensitive to **salinity**, primarily during germination and emergence stages; once the plants are established, they can tolerate higher levels of salinity.

Further reading on salinity management for growers: https://www.soilwealth.com.au/resources/fact-sheets/soil-nutrition-and-compost/managing-salinity-in-vegetable-crops/

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Nutrient needs of onion crops

A good nutrition program for onions will provide nutrients to the upper 15-40 cm of the soil over the entire growing season, adjusted to soil reserves, yield target and physiological growth stages. Soil analyses are the best indicators for macro- and micronutrient needs; dry tissue or plant sap analyses combined with cropping and soil history are the best indicators of nutrient needs during the growing season.

General information for Australian onion producers to help with nutrient budgeting

60 tonnes of onion bulbs harvested per hectare may remove more than 100 kg/ha of nitrogen (N), around 20 kg/ha of phosphorus (P) and 120 kg/ha of potassium (K). Recommendations for onion production suggest that, on average, a total supply of 120 to 140 kg N, 22–26 kg P and 150 kg K per hectare would be required from soil reserves and fertilisers together. Peak N, P, K and sulphur (S) uptake occurs during 15 to 60 days after emergence.

Some nutrient removal rate ranges (kilograms per tonne [kg/t] or milligrams per kilogram [mg/kg]) of onion bulb gross yield produced, as cited in international literature, are provided below and in Figure 1. Rates vary, in part due the differences in measuring removal. In some literature, removal rates describe the total uptake of the nutrient into roots, bulbs and foliage; in other literature, removal is determined via the nutrient content in the fresh or dry bulbs. Most research publications also do not mention whether yield figures refer to fresh bulb or dry bulb weights or to total or marketable yield. Information on variety and growing conditions if often not comprehensive. As a guide, about 80% of the nutrients present in the plant at harvest are present in the bulb; the remainder is present in tops.

N:	2.0 to 5.0 kg/t	K:	1.5 to 4.5 kg/t	Mg:	0.1 to 0.5 kg/t
P:	0.2 to 1.0 kg/t	Ca:	1.0 to 3.5 kg/t	S:	around 0.6 kg/t

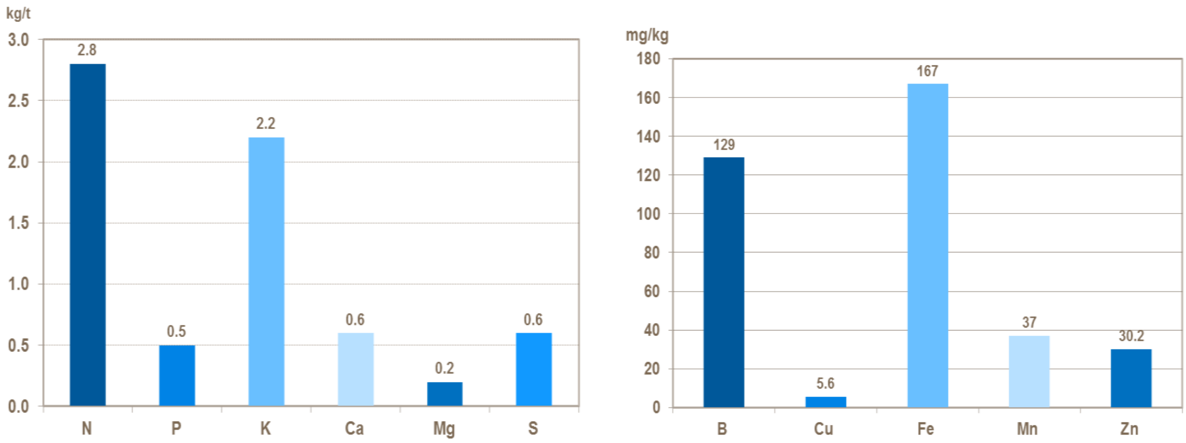

Figure 1: Example of nutrient removal rates of onions, major elements are shown in kg/t and trace elements in mg/kg (same as ppm).

Source of graphs: Bender B.A. 1993 in W.F. Bennett (Ed.), Nutrient Deficiencies and Toxicities in Crop Plants, The American Phytopathological Society, St. Paul., MN (1993), pp. 131-135.

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Pire et al. (2001) reported the following removal of N:P:K and Ca from soil by different portions of onion plants at harvest. Table 2 shows the reported mean values and variability as standard deviation (SD).

Table 2: Nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca) removal of onion crops

Plant parts	N(kg ha^{-1})	P(kg ha^{-1})	K(kg ha^{-1})	Ca(kg ha^{-1})
Bulb	113.12 ± 9.33	22.85 ± 4.08	100.7 ± 15.81	71.28 ± 10.91
Leaf	5.19 ± 1.02	0.52 ± 0.11	9.81 ± 2.11	5.88 ± 1.35
Root	0.33 ± 0.08	0.06 ± 0.01	0.21 ± 0.06	0.47 ± 0.09
Whole plant	118.64	23.43	110.72	77.63

Source: Pire, R., Ramirez, H., Riera, J., & Gómez de, T.N. (2001). Removal of N, P, K and Ca by an onion crop (Allium cepa L.) in a silty-clay soil, in a semiarid region of Venezuela. Acta Horticulturae, 555, 103–109. doi:10.17660/ActaHortic.2001.555.12

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2 Determining nutrient needs

The mineral nutrient requirements of onion crops depend on a range of factors, such as variety, plant density, production environment, soil fertility, fertilisation methods and managing applied fertiliser via irrigation. Therefore, this section and supporting information in the Appendices to this guide support an approach to determining site-specific nutrient needs, rather than providing recipes.

The aim of nutrient management is to supply nutrients in a timely manner to maximise crop yield and quality. Crop nutrient uptake at different growth stages can be calculated by measuring the crop biomass (dry matter weight of whole plant samples) at that stage and multiplying by the crop nutrient concentration (via dry tissue test). These results can be used to estimate the total supply of available nutrients needed to grow the crop under good management.

The basic concept of crop nutrition is to balance soil fertility so that pH, EC and soil nutrients are in a satisfactory range for the soil type and soil condition.

The nutrients that are required to produce the crop are added during the growing season under consideration of the target yield and expected growing conditions. The approach is explained in the following section.

One major aim of nutrient budgeting is to optimise yield and quality and achieve a high nutrient use efficiency. This approach will prevent nutrients from being lost from the production system and potentially causing environmental harm.

How much of each nutrient is needed?

During harvest, nutrients are removed from the system. If the soil is in balance, only what is removed with harvest needs to be replaced via mineral or organic fertilisers. Thus, crop removal figures can be used as a starting point for nutrient budgeting. Various nutrient budgeting tools are available (see Resources).

1. Use a soil test to determine nutrient deficiencies in the soil (main rootzone depth) and the amount of nutrients required to balance the soil, so that all nutrients are within a satisfactory range in the soil.

2. Determine nutrient removal, i.e., the amount of all nutrients removed with harvest in kilograms per tonne (kg/t), based on the anticipated total yield, and multiply by the anticipated yield in tonnes per hectare (t/ha) to decide how much of each nutrient is required to replace the removed nutrients (kg/ha).

To convert mg/kg to kg/ha, multiply the soil test value in each sampling layer by the depth of the soil sample (millimeters), then multiply by the bulk density (g/cm3) and divide by 100, then add up the values for each layer to arrive at nutrient content in kg/ha to the total soil depth sampled.

Example for one layer sampled to 20 cm:

Test value	100	mg/kg
Sampling depth	200	mm
Bulk density	1.2	g/cm3
Result	240	kg/ha

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This approach to nutrient budgeting based on soil reserves and removal rates only works if:

- The soil is balanced (see step 1. above) and does not have major deficiencies,
- The soil structure is good, i.e., there is no compaction or surface sealing that will affect root development,
- There are no issues with soil borne diseases that will affect root health,
- There are no major interfering factors such as:
  - Salinity or sodicity, that will interfere with nutrient uptake and root growth and function
  - High levels of iron, aluminium, manganese or calcium that will lead to chemical fixing of phosphorus
  - High C/N ratio (> 25/1, i.e. more than 25 g C to 1 g N) that will lead to biological nitrogen fixing.
- There are no subsoil constraints that will affect root growth.

"The crop removal approach" is a guide[1]; it does not account for inefficiencies in nutrient availability to the crop or root access, nutrient competition due to imbalances, leaching losses, additions of N via mineralisation, or nutrient fixing such as biological N fixing when the C/N ratio is high or P fixing by aluminium, iron, manganese or calcium. It should be used to estimate the basic nutrient needs. Adjustments can then be made by considering the abovementioned factors, as well as soil conditions and anticipated weather conditions during the growing period.

Never wait for nutrient deficiencies to occur to 'diagnose' nutrition needs. If they occur, the crop has been damaged and there will be a yield and or quality penalty. Soil and plant testing can be used to identify deficiencies and imbalances before they occur.

In summary, the approach to managing onion nutrition is to develop a site- specific nutrient budget based on:

- Soil testing data, yield targets and crop removal rates
- Split nitrogen applications according to needs at different growth stages
- Monitoring of nutrient uptake via plant testing to be able to adjust topdressing rates and or apply additional nutrients via foliar applications or fertigation
- A good understanding of the function and positive or negative aspects of different fertiliser products and application methods as well as knowledge of the impact of soil amendments
- Regional experience that is based on a good understating of onion nutrition management.

The following Appendices may help with nutrient budgeting and management:

Appendix 1: Nutrient composition, functions and mobility

Appendix 2: How do nutrients get from the soil into the plant?

Appendix 3: Nutrient interactions

Appendix 4: pH and liming

Appendix 5: Overview of fertiliser nutrient composition and concentration

Appendix 6: Nutrient stewardship – how to get the most out of fertilisers and avoid losses

Appendix 7: Resources

Appendix 8: Further reading

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3 Nutrition strategies for onions

Refer to Appendices 1, 2 and 3 for more information about nutrients, nutrient interactions and their movement in soils and plants. Appendix 5 gives an overview of fertiliser composition and concentration, and Appendix 6 explains how to get the most out of applied fertilisers and avoid losses (Nutrient Stewardship).

Soil factors affecting nutrient availability and uptake

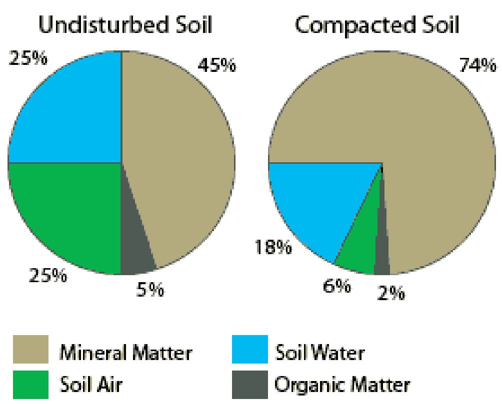
All soil is made up of air, water, decayed plant materials, numerous kinds of living and/or dead organisms (organic matter), and mineral matter (sand, silt, clay). These soil components determine the physical, biological and chemical properties of a soil. Their combination is an indicator of soil condition or health and productivity potential.

The soil composition can be dramatically changed by soil management, especially by heavy traffic, particularly when the soil is too wet. Soil components most easily changed are the amounts of soil air and water, followed by all types of organic matter. The make-up and condition of the soil affect nutrient availability and uptake because it affects the 'living conditions' for roots and soil life which is important for soil and crop health.

Under ideal conditions, topsoils are made up of 50% solid matter (minerals, organic matter) and 50 % pores. Pores are of different sizes – i.e., large pores for drainage, medium pores to hold plant available water and a minimum volume of small pores that tightly hold on to water so that it is not available to plants. For optimal plant growth, pores contain half air and half water (**Figure 2**).

Many Australian soils naturally have quite low organic matter (OM) levels. The hotter or colder and dryer the climate, the lower the OM levels. The aim for growers should be to maintain OM matter levels as close to the natural level as possible.

Figure 2 also shows an example for a compacted, poorly structured soil. There the total pore space is reduced, and this usually means that the large, draining pores have been destroyed and organic matter has been lost, usually due to soil management. Compaction leads to reduced root penetration, water infiltration and drainage, and increase the risk of run-off and erosion. The soil's water holding capacity is reduced. Compacted soils become too wet and too dry more quickly than well structured, friable soils. Crops under these conditions are more difficult to manage because they are more prone to pests and diseases, and/or they suffer from nutrient imbalances or deficiencies.



A nutrition and irrigation schedule program must take soil composition and conditions into account. Compacted soils most likely need more frequent application of smaller amounts of water and potentially nutrients, and closer monitoring.

Figure 2: Example of the composition of an undisturbed soil (ideal) and compacted soil (source: https://www.nrcs.usda.gov/wps/portal/nrcs/mt/water/resources/nrcs144p2_057472/)

[1] https://www.horticulture.com.au/globalassets/hort-innovation/resource-assets/vg14025-pre-harvest-effects-on-the-quality-of-baby-spinach.pdf

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Soil acidity or alkalinity (pH)

If soil test results show a pH below 6.0, the recommendation is to apply and work in lime (calcium carbonate) or dolomite (calcium-magnesium carbonate) two to three months before final soil preparation to bring the pH to the optimum range of pH 6.2 to 6.5. It is essential to apply sufficient lime regularly to keep the soil pH above 6.0. If the pH must be increased by more than one pH point, this should be done over two years rather than using a massive amount of lime in one 'king hit'. Refer to Appendix 4 for information on pH and liming. Gypsum (calcium sulphate) does not change the soil's pH.

Low pH can cause nutrient deficiencies during the growing season and reduce yield. Also, high rates of urea- or ammonium-based fertiliser cause the pH to drop during the growing season. Calcium (Ca) and phosphorous (P) deficiencies can often be linked to low pH, even though soil tests indicate adequate levels. Nutrient deficiencies due to low pH can be difficult to correct during the growing season via side dressing. Foliar application can help to reduce stress due to nutrient deficiencies, to some degree.

Table 3: Kilograms (kg) lime high purity lime needed per kg nitrogen (N) applied

NITROGEN FERTILISER	kg LIME NEEDED PER kg N APPLIED
Urea (46% N)	2
Ammonium nitrate (34% N)	2
Diammonium phosphate (DAP) (18% N)	3.5
Sulphate of ammonia (21% N)	5.5
Mono-ammonium phosphate (MAP) (11.3% N)	5.5
Nitrate based fertilisers (e.g., calcium nitrate or potassium nitrate)	0

The data in Table 3 assumes that a proportion of nitrogen is not taken up by the crop, which is a farming reality.

Salinity

Many Australian soils are affected by salinity. Reasons for this include the use of saline irrigation water, rising water tables that carry salts to the soil surface or Cl deposits from the air in coastal areas.

Onions are relatively sensitive to soil salinity, which is typically measured via electric conductivity (EC). A high EC means that the soil solution or water tested has a high concertation of salts, commonly sodium chloride (NaCl) salt. Table 4 provides information on the potential effect of high soil EC on onions. The EC was measured in a saturated paste extract (ECe) as is the common practice when reporting salinity tolerance limits in soils. This is important to note as most soil tests provide results for EC measured in a diluted extract (1 part soil, 5 parts water, reported as EC 1:5). This gives an approximately 10 times lower EC value.

Refer to: https://www.soilwealth.com.au/resources/fact-sheets/soil-nutrition-and-compost/managing-salinity-in-vegetable-crops/

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Table 4: Effect of soil salinity (ECe) on onion yield

Conductivity (ECe) (mmhos/cm) or (dS/m)	1.2	1.8	2.8	4.3	7.5
Potential yield decrease %	0	10	25	50	100

Source: Shannon, M.C. and Grieve, C.M. (1999) Tolerance of Vegetable Crops to Salinity. Scientia Horticulturae, 78, 5-38.

Soil chloride levels are a good indicator of whether salinity is caused by sodium chloride (NaCl) or other electrolytes such as sulphur, which can occur from overuse of gypsum.

Macro nutrients (major elements)

Nitrogen (N)

Onion crop nitrogen (N) removal figures are reported to be in the range of 2 to 5 kg N per tonne bulb yield. Crop N uptake rates can range from 1.2 to 3.6 kg per hectare per day. Most N is taken up as nitrate.

Nitrogen has many functions in plants and is needed to build biomass. It is found in all plant cells, e.g., in plant proteins, growth regulators, and chlorophyll. When applied to soil as urea or in ammonium (NH4) form, it is converted to mineral nitrate, the preferred form for uptake by most plants. Plants can also take up ammonium from the soil. Refer to Appendix 5 and Table 10 to find the names of common nitrogen fertilisers that contain ammonium.

N plays an important role in the development of onion bulbs, primarily by affecting leaf growth (leaf bases develop into onion scales). Therefore, onion crops require adequate supply during the vegetative, leaf development phase, before bulbing. Excessive and late-season application of nitrogen, even during bulbing, increases the expansion of leaves. This excessive or late N delays maturing of bulbs and reduces storability. It also causes bolting, split root bases, increases susceptibility to pests and diseases in the field and reduces storage life due to skinning, bruising and diseases. post-harvest.

Nitrogen is mineralised to ammonium and nitrate from organic matter and then becomes available to plants the same as fertiliser N. This process is mainly depended on soil aeration, temperature and moisture. Organic matter quality, soil texture, pH and electric conductivity (EC) may have a minor influence if they affect microbial activity. The rate of mineralisation increases exponentially once soil temperatures exceed 10oC and decline somewhat above temperatures of above 35 oC. The higher the organic matter content, the higher the mineralisation potential under otherwise identical conditions. This means soils high in organic matter require less applied fertiliser than soils low in organic matter. An estimate of N from mineralisation of organic matter should be included in nitrogen budgets for onion crops. This can be done via calculations, lab simulations or monitoring of available soil N (nitrate N and ammonium N) in the rootzone prior to topdressing, when soils have warmed to above 12-14oC. Monitoring of crop N uptake levels (e.g., via sap testing) can provide information on the N status of crops to ensure they are not over or undersupplied.

Adequate N from (measured and estimated) soil reserves plus fertilisers in split applications are required to produce the healthy foliage that support bulb growth and protect bulbs from sunburn.

N in excess to crop needs is easily leached out of the rootzone by heavy rain and irrigation, resulting in losses to crops and soil acidification (Table 3). High N applications during early growth stages are especially prone to losses. If nitrogen is applied too late in the season, it may delay maturity and cause double centers. N budgeting, monitoring and split applications will prevent excess N affecting crops or getting lost from the production system as well as N deficiencies.

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The use of ammonium-based fertilisers can increase the incidence of some diseases (e.g., Fusarium and Phytophthora root rots), whereas nitrate-based fertilisers generally have the opposite effect. Ammonium fertilisers and urea generally decrease soil pH over time, particularly in soils with low buffering capacity; nitrate fertilisers tend to either slightly increase soil pH or have no effect (Table 3).

Strategies for N management of onion crops

- Determine crop N requirement based on removal rate and yield target, e.g., a 70-tonne crop would remove 210 to 350 kg N/ha based on a removal of 3-5 kg/t. Not all of this amount has to be applied via fertilisers.
- When determining N fertiliser application rates, credit N from non-fertiliser sources:
  - Available N measured in a preplant soil test
  - N in irrigation water
  - N potentially mineralised during the growing season, which can be estimated using common mineralisation rates for crop residues and organic matter or via a lab analysis of mineralisable nitrogen.
- Minimize preplant N fertiliser application; incorporate not more than 20% the required nitrogen (based on soil testing and yield prediction) prior to planting, apply the remainder in two or three split applications
- Use slow or controlled-release N fertilisers
- Balance N with other nutrients, including trace elements
- Apply most or all of the N fertiliser as side-dress applications or through sprinkler or drip irrigation, use foliar applications to eliminate minor deficiencies
- Adjust rates per application to crop needs (removal rates) by growth stage
- Where technically feasible, use irrigation practices to minimise leaching losses by water moving below the rootzone
- Use plant tissue or sap tests and/or soil tests for available N to more precisely assess the need for and amount of fertiliser needed in season
- Grow deeper rooted crops or cover crops after onions to recover N leached beyond the rootzone.
- Look after organic matter and soil structure (no compaction) to optimise nutrient uptake conditions
- Use the final nitrogen application at least four weeks prior to harvest.

Opportunities to reduce N losses

Nitrogen fertiliser is lost by gaseous losses and leaching. In sandy soils, N mostly leaches, but in clays and duplex soils, gas is emitted.

- **Tillage:** Reducing tillage and retaining plant residues such as stubble, improves drainage and soil structure via aggregation (the way soil particles bind together) and reduces the risk of waterlogging which leads to gaseous N losses (denitrification). Tillage exposes soil aggregates and makes carbon more accessible to micro-organisms. There are higher CO_2 emissions after tillage, indicating organic matter losses. Stubble breakdown may fix N if the carbon to nitrogen ratio is above 22/1. A light application of nitrogen can improve stubble breakdown.
- **Organic Matter:** Retaining residues will improve soil organic matter, important for soil structure, nutrient holding and soil life and act a pH buffer.
- **pH:** Maintaining a favourable pH for crops and microbial activity.

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- **Cover crops:** A short-term cover crop grown at the end of the season is an organic source of N which can soak up any excess nitrogen and 'store' it for later release to the next crop.
- **Irrigation:** Applying small amounts of water more often promotes plant growth and better matches water demand to crop growth and uptake of water and nutrients, reducing waterlogging and thus N losses.
- **Drainage:** Improving drainage in high rainfall areas and under irrigation reduces opportunities for waterlogging and nitrogen losses.

Nitrogen use efficiency

The crop's nitrogen use efficiency (NUE), calculated after harvest, shows how much of the applied N has been used by the onion crop. It therefore shows whether fertiliser may have been wasted or whether more should have been applied.

The NUE partial nutrient balance (also known as output-input ratio or removal to use ratio) is calculated NUE% as follows:

NUE% = N removed / N applied x 100

This method does not consider N from sources other than applied N (e.g., N fixed by legumes, mineralisation of organic matter) or N losses (e.g., N_2O gas, NH_4 volatilisation, leaching, runoff).

A high NUE% of >100%, indicates that more N is being removed than is being applied and the plants access N from the 'organic pool' or residual N from fertiliser applications to a preceding crop. Depleting the 'organic pool' can result in nitrogen deficiencies at a later stage, if not replenished.

A low NUE%, e.g., <70-60% (depending on crop), indicates that less N is being removed than has been applied; applied N is left in the soil and may be lost. As a 'rule of thumb', residual available (nitrate and ammonium) nitrogen in the soil after harvest should not exceed 50 kg/ha in the onion's root zone. If NUE% is low it could indicate excessive use of fertilisers and or irrigation or issues with crop health – i.e., the crop has not grown to potential due to lack of water or pests or diseases, so that a standard fertiliser program provided too much N.

Phosphorus (P)

Onion crop phosphorus (P) removal figures removal figures are reported to be in the range of 0.2 to 1 kg P per tonne bulb yield.

Readily available P is essential for rapid root development and early crop growth during the establishment phase and energy transfer in plants during the entire crop development; it accelerates maturity. Phosphorus deficiency reduces bulb size and can delay maturity.

Very few Australian soils contain enough soil phosphorus for sustained crop production without added fertilisers or soil amendments. The most common phosphorus sources are superphosphate-based fertilisers (e.g. single super phosphate, SSP 7-9% P or triple superphosphate, TSP 44-46% P). The key difference between single superphosphate and triple superphosphate is that single superphosphate is produced from phosphate rock and sulfuric acid, whereas triple superphosphate is produced from phosphate rock and phosphoric acid. SSP will have an initial acidifying effect but should not have a lasting effect on soil pH. TSP can lower the pH of soils, depending on soil conditions and fertility but generally, P fertilisers are not as acidifying as nitrogen products that contain ammonium or urea.

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Monopotassium phosphate (MKP) or liquid P fertiliser formulations may provide a more readily available P source than traditional solid P fertilisers. Details on availability and best use of liquids need to be checked with the fertiliser supplier or agronomist.

Biosolids, fish waste and all manures contain phosphorus; manure from grain-fed animals is a particularly rich P source. Composts are generally low in nutrients, including phosphorus, unless manure, fish waste or biosolids are a feedstock. Composts can help with P cycling and availability via improving microbial activity.

P is not readily available at low soil temperatures, even if soil test levels are adequate. Liquid P sources can be used to overcome the issue, if economically and practically feasible.

Under most conditions, all the P can be applied preplant and incorporated before transplanting. If P is applied during soil preparation to P fixing soils that are high in iron, aluminium (low pH) or high in calcium (high pH) too far ahead of planting, it may not be available throughout the season. A proportion of the applied P may be fixed already before planting. In these soils preplant P should be applied as close to planting as possible. Banding of P at panting is the best way to avoid P fixing. Top dressing, foliar applications or fertigation where possible may be required during the season. Plant or soil testing should be used to determine P needs during the season.

Given the nature of phosphorus availability from soils, P replacement rates need to be higher than removal rates (around 2-3 times the removal rate, if the soil is not deficient), epically in heavier soils compared to light, sandy soils. P-fixing soils may require higher rates. Good organic matter levels for the given soil type and climate, and good soil structure will improve P availability and uptake. The reason for this is that organic matter and good soil structure support microbial activity, mycorrhiza association and general root health and function.

Potassium (K)

Onion crop potassium (K) removal figures are reported to be in the range of 1.5 to 4.5 kg K per tonne bulb yield. This is similar to the N uptake rates.

K is required for plant water relations and water use efficiency. It regulates stomata function, supports cell-wall formation and energy transfers in plants. Potassium can increase vigour and disease resistance and helps form and move starches, sugars and oils in plants, and can thus improve quality. According to research, potassium application can significantly increase the dry weight of onion tops and bulbs and bulb diameter. Potassium sulphate achieved good results.

Potassium is low or deficient on many of the sandier soils. High potassium removal can occur on soils used for high yielding vegetable crops (potatoes, brassica crops) and intensive pastures. K is subject to leaching from heavy rainfall or irrigation in lighter soils. Therefore, it is best to split K applications by incorporating 30% to 50% of the required K before planting and splitting the remainder in one to two side dress applications. A low K level makes plants more susceptible to cold injury and fungal leaf disease.

Muriate of potash (potassium chloride) and sulphate of potash (potassium sulphate) are the most common sources of potassium; other K fertilisers are for instance potassium nitrate and mon potassium phosphate (MKP). Nearly half of muriate of potash (potassium chloride) fertiliser is made up of chloride. Onions require only very small amounts of this trace element. Especially in saline soils, which are already high in chloride, muriate of potash (potassium chloride) should not be used.

Sulphur (S)

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Onion crop sulphur (S) removal figures are reported to be around 0.6 kg S per tonne bulb yield. Most S is taken up as sulphate.

Sulphur (S) is an essential element for plant growth. It is a constituent of all amino acids in plant proteins and is involved in energy-producing processes in plants. It is responsible for many flavour and odour compounds in plants such as the typical smell and pungency of onions (or cabbage). Some of the S compounds responsible for pungency can inhibit the growth of fungi and bacteria and have been shown to reduce storage losses of sweet, short-day onions grown in Georgia, USA. Sulphur has also been reported as important for higher yield and quality of onions.

Early applications of sulphur are advisable and should be based on soil testing. The required rate should be applied in two or more split applications. If the aim is to minimise pungency, fertilisers that contain S should not be applied after commencement of bulbing. Research has shown that pungency (pyruvate analysis) of mature onions increases with high rates of S or whenever S applications are made after early bulbing. Total S rates should not exceed than 40-60 kg/ha.

Sulphur deficiency is not a problem in soils high in organic matter, but it leaches easily. In coastal areas, sea 'spray' is a major source of atmospheric sulphur, especially if the wind comes from the sea. Superphosphate fertilisers sulphate of ammonia and potassium sulphate are common fertiliser sources providing S to crops. Sulphate of ammonia lowers the soil's pH more than many other fertilisers (but like MAP) because it contains two acidifying elements (refer to Table 3).

Gypsum (calcium sulphate) is often used to improve the friability of clay soils. It does increase the soil S level and, with frequent use over time, the electrical conductivity (EC) of the soil. This can be an issue if soils already have a high EC (salinity).

Calcium (Ca)

Onion crop calcium (Ca) removal figures are reported to be around 1 to 3.5 kg Ca per tonne bulb yield.

Calcium is essential for root health, growth of new roots and root hairs, and the development of leaves as well as building strong cell walls. Adequate calcium levels in the plant are important for good storage performance.

Calcium uptake is driven by transpiration, i.e., the loss of water through leaves (passive transport). This means that calcium only moves upwards with water, not from leaves to roots (no active transport).

Ca is generally in short supply in acid soils. Lime, gypsum, dolomite, and superphosphate (a mixture of calcium phosphate and calcium sulphate) all supply calcium to the soil but do not provide readily available Ca to the soil solution. Lime and dolomite raise the pH, gypsum improves soil structure in clay soils but does not change the pH.

Lime is often seen as the cheapest option for increasing soil Ca levels, and it is important for increasing the pH of acid soils (via its carbonate component), improving soil structure and microbial activity (as part of the pH and structure effect). However, soluble Ca should be provided especially early in the season, e.g., via liquid fertilisers or calcium nitrate. When using calcium nitrate, care must be taken to not oversupply nitrate N to young crops when uptake is low. Calcium nitrate may be a good topdressing fertiliser.

Magnesium (Mg)

Onion crop magnesium (Mg) removal figures are reported to be around 1 to 1.5 hg Mg per tonne bulb yield.

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Magnesium (Mg) levels in the soil must be adequate for good onion growth. Magnesium is a key component of the green pigment chlorophyll. It is vital for photosynthesis (the conversion of the sun's energy to energy for the plant). Deficiencies occur mainly on sandy, acid soils in high rainfall areas, especially if used for intensive horticulture or dairying. Heavy applications of potassium in fertilisers can also produce magnesium deficiency due to cation competition.

Magnesium deficiency in soils can be overcome with dolomite (magnesium-calcium carbonate, slow availability), magnesite (magnesium oxide) or Epsom salts (magnesium sulphate).

Micronutrients (trace elements)

Applications of micronutrients are not recommended unless a reliable soil or plant tissue or sap test indicates a need.

Boron (B)

Boron, together with calcium, helps with the formation of cell walls in rapidly growing tissue. Deficiency reduces the uptake of calcium and inhibits the plant's ability to use it. It is chronically deficient in some Australian soils used for horticulture.

B can be reasonably easily applied to the soil via borax or calcium nitrate plus B. Do not exceed the recommended amount since boron can be toxic to onions. Applications need to be based on soil testing results. Foliar applications work as well, and rates must not exceed label recommendations because B will be phytotoxic if oversupplied. Plant testing can provide information on how much to apply.

Boron uptake is driven by transpiration, i.e., the loss of water through leaves (passive transport). This means that boron only moves upwards with water, not from leaves to roots (no active transport).

According to research trials, application of boron can increase bulb size, yield and quality of onions. However, soil plant testing should be used to confirm the need for B fertilisers to avoid phytotoxicity.

Zinc (Zn)

Zinc (Zn) helps in the production of a plant growth regulators responsible for stem elongation and leaf expansion. It is readily available in acid soils but is easily outcompeted for uptake by iron in volcanic soils. If zinc levels determined by soil testing are low addition of zinc sulphate can be used to increase soil levels. Zinc is usually added in the preplant fertiliser. Crops can be sprayed with foliar zinc fertilisers if required based on plant testing. Chelated products will be most efficient.

Onions are sensitive to zinc deficiency. Applying zinc, when needed can increase the yield and quality of onions bulbs. Foliar applications, alone or in combinations with other trace elements where needed, have been shown to be effective.

Trials from the USA showed that application of manure or compost to other crops in rotation with onions might reduce or eliminate deficiencies of Zn and other micronutrients in onions. The quality and composition of organic amendments such as manures and composts vary widely. Therefore, they should not be used without prior testing.

Excessive amounts of Zn can be toxic, so apply only if needed. Zn can compete with other trace metals (e.g., copper, manganese) for uptake.

Copper (Cu)

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Copper is an essential constituent of enzymes in plants and can be readily available in some soils, although it can be deficient, especially in red soils. Overuse of another trace element, e.g., molybdenum, can cause copper deficiency in animals. Overuse can cause toxicity and reduce uptake of other trace metals (e.g., Mn).

Iron (Fe)

Iron is a constituent of many plant compounds that regulate and promote growth. It usually is readily available in naturally acid soils. Deficiencies can be addressed via foliar applications. These are commonly applied as a complete trace element mix.

For example, it has been reported that, in a trial, foliar application of $ZnSO_4$ (0.5%) and $FeSO_4$ (1.0%) influenced the yield and quality of onions. In another trial, a combined application of NPK and foliar micronutrients (Fe + Zn + Cu) at rates of 300, 100 and 50 ppm (mg/L), respectively significantly increased bulb yield compared to sole application of NPK.

Manganese (Mn)

Manganese helps with photosynthesis. It is freely available in naturally acid soils, often in toxic amounts in very acid soils, but can be deficient in sandy soils. Toxicity is remedied with lime.

Molybdenum (Mo)

Molybdenum helps bacteria and soil organisms convert nitrogen from the air to soluble nitrogen compounds in the soil, so is particularly needed by legumes. It is also essential in the formation of proteins from soluble nitrogen compounds taken up from the soil or leaves.

Molybdenum deficiency is prevalent in many acid soils but can be remedied easily with applications of Mo super, molybdenum trioxide (applied during inoculation and lime pelleting of legume seed), or sodium molybdate (sprayed on emerging and young plants).

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4 Crop nutrition monitoring

For generations, growers, agronomists, and scientists have used visual symptoms to identify nutrient deficiencies. However, waiting for deficiencies means that the crop will not reach its full potential. Nonetheless, monitoring for symptoms can be useful.

General deficiency symptoms include stunted growth, chlorosis, interveinal chlorosis, purple or red discoloration and necrosis. Deficiencies of mobile nutrients first appear in older, lower leaves, whereas deficiencies of immobile nutrients will occur in younger, upper leaves. Nutrient toxicity is most often the result of over-application, with symptoms including abnormal growth (excessive or stunted), chlorosis, leaf discoloration and necrotic spotting. When in excess, many nutrients will inhibit the uptake of other nutrients, thus potentially causing deficiency symptoms to occur as well.

- Deficiency symptoms on older leaves mean that a mobile element (N, P, K, Mg, Mn) is in short supply
- Deficiency symptoms on young leaves mean that an immobile element (Ca, S, Fe, Cu, Zn, B, Mo) is in short supply.

Diagnosing high value crops via symptoms is flawed. Once a deficiency is visible, the crop has been set back in development and this set back cannot be recovered, even if the symptoms can be alleviated.

Symptoms of poor growth or abnormalities in leaf colour are hard to interpret. Several factors other than nutrient deficiencies can cause similar symptoms.

Precautions in identifying nutrient stress or deficiency symptoms are summarised in the following:

- Many symptoms appear similar. For instance, Mn and Fe deficiency symptoms can look very alike, S and N deficiency look similar depending upon plant growth stage and severity of deficiencies.
- An oversupply of one nutrient can disguise a deficiency in another, e.g., a plant high in magnesium looks green, even if low in nitrogen.
- Multiple deficiencies and/or toxicities can occur at the same time. More than one deficiency or toxicity can produce symptoms, or possibly an abundance of one nutrient can induce the deficiency of another (e.g., excessive P causing Zn deficiency).
- Crop species, and even some cultivars of the same species, differ in their ability to adapt to nutrient deficiencies and toxicities. For example, corn is typically more sensitive to a Zn deficiency than barley and will show Zn deficiency more clearly.
- Pseudo (false) deficiency symptoms (visual symptoms appearing similar to nutrient deficiency symptoms). Potential factors causing pseudo deficiency include, but are not limited to, disease, drought, excess water, genetic abnormalities, herbicide and pesticide residues, insects, and soil compaction. moisture stress, high salinity, herbicide damage or disease caused by bacteria, fungi or viruses.
- ‘Hidden hunger’; Plants may be nutrient deficient without showing visual clues.
- Field symptoms appear different than ‘ideal’ symptoms. Many of the plant deficiency symptoms shown in photographs were grown under controlled nutrient conditions which just one nutrient in low supply; and deficiency/toxicity symptoms observed in the field may or may not appear as they do in photos. Experience and knowledge of field history are excellent aids in determining causes for nutrient stress.

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- Between the time a plant is nutrient deficient (hidden hunger) and visual symptoms appear, crop health and productivity may be substantially reduced, and corrective actions may or may not be effective.

For a general guide to deficiency and toxicity symptoms, refer to Appendix 1.

For those who want to intervene before symptoms appear, information on plant analysis can be found in a guide that covers laboratory-based plant nutrient analyses, specifically dry matter analysis and sap analysis. It can be accessed here:

https://www.soilwealth.com.au/resources/articles-and-publications/plant-analysis-for-vegetable-crops-a-practical-guide-to- sampling-analysis-and-interpretation/page8image55419328page8image55421824page8image55417600page8image55413760

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Appendix 1: Nutrient composition, functions, and mobility

Elemental composition of plants

Sixteen elements have been identified as essential for plant growth and development. Three of the elements (carbon, hydrogen, and oxygen) are derived from air and water and thirteen of them (nitrogen, phosphorous, potassium, calcium, magnesium, sulphur, iron, manganese, boron, zinc, copper, molybdenum and chlorine) are derived from soils and, in agriculture, are also provided via soil amendments and fertilisers.

If any of the 16 essential elements are not available or are in low or too high supply, normal plant functions will be affected, and characteristic symptoms will develop if the deficiency is severe or has been present for a while.

Soils and soil amendments are a source of beneficial nutrients such as cobalt, nickel, selenium, aluminium, silicon and sodium. They are not required by all plants but can promote plant growth and may be essential for some groups of plants. These beneficial elements have reportedly enhanced resistance to biotic stresses such as pathogens and herbivory, and to abiotic stresses such as drought, salinity, and nutrient toxicity or deficiency. The beneficial effects of low doses of Al, Co, Na, Ni, Si and Se have received little attention compared to toxic effects that typically occur at higher concentrations. Recently, some scientists have proposed that Ni and Si are essential trace elements.

Plants may contain traces of a range of other elements than listed above (e.g., vanadium, chromium, lead, silver, mercury, iodine, arsenic, fluorine) depending on where they are grown. However, their role is still unclear, and many scientists assume that these elements have no physiological function.

The elemental composition of plant dry matter is:

Carbon (C) -	40-50% (from air)
Oxygen (O) -	42-46% (from air and water)
Hydrogen (H) -	5 -7% (from water)
Mineral elements -	5-10% (from soil or foliage in crops)

The macronutrients carbon, oxygen and hydrogen are used in very large quantities; they are fixed through photosynthesis:

- Carbon is the ‘backbone’ of most biomolecules, including proteins and carbohydrates (glucose, cellulose)
- Hydrogen is a building block of carbohydrates; the H proton creates a gradient to help drive electron transport chain in photosynthesis and for respiration
- Oxygen is a component of many organic and inorganic molecules in plants, plants produce oxygen gas (O2) during photosynthesis and require O2 for respiration (i.e., use energy for growth).

Mineral nutrients are plant nutrients other than carbon, oxygen and hydrogen. Table 5 provides information on mineral elements and focusses on essential nutrients.

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For information on nutrient mobility in soil refer to Appendix 2 for information in interactions, refer to Appendix 3.

Table 5: Nutrient element functions, mobility, uptake, deficiency and excess

MAJOR ELEMENTS						
NUTRIENT	MAIN FUNCTION	MOBILITY IN PLANT	MAIN UPTAKE MECHANISM & (UPTAKE FORM)	POTENTIAL UPTAKE INTERFERENCE OR PROBLEMS	DEFICIENCY SYMPTOMS	EXCESS SYMPTOMS
Nitrogen - N	Protein synthesis; N is the main building block of proteins having a major effect on growth & quality	High – transferred to younger plant parts when required = deficiency symptoms on older leaves	Mass flow (NO3 and NH4)	Losses may occur due to NO3 leaching, denitrification, N immobilisation or fixation of NH4 in clay minerals	Low vigour, yellowing of older leaves	Blue green, large, soft foliage, disease susceptibility, lodging, may lead to relative low K, relatively small root system
Phosphorus - P	Energy transfer (early root growth, fruit and seed set)	High – transferred to younger plant parts when required= deficiency symptoms on older leaves	Diffusion (very slow) Root interception (HPO4, H2PO4)	Poor root system reduces uptake potential. High Ca, Fe or Al concentration in soil (high or low pH respectively)	Poor seedling establishment, root development and fruit and seed set, stunted growth, purple discolouration of older leaves	Not found to be a problem
Potassium - K	Carbohydrate (starch & sugars) and protein synthesis, water balance control (root intake, loss through stomata), electrical balance	Mobile= deficiency symptoms on older leaves	Diffusion, some mass flow	Competing with other cations (Mg, Na, Ca or NH4), fixation of K in clay minerals	Yellowing of margins and tips of older leaves, progressing to white-brownish spots and then 'scorching' (necrosis) of leaf margins	Ca or Mg deficiency possible, may reduce sugar and starch in root crops

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MAJOR ELEMENTS [CONT.]						
NUTRIENT	MAIN FUNCTION	MOBILITY IN PLANT	MAIN UPTAKE MECHANISM & (UPTAKE FORM)	UPTAKE INTERFERENCE OR PROBLEMS	DEFICIENCY SYMPTOMS	EXCESS SYMPTOMS
Calcium (Ca)	Component of structural organs, protein synthesis, ion uptake	No relocation within the plant, moves only with transpiration = symptoms on growing tips	Root interception, some mass flow (Ca)	Other cations (K, Mg), Ca leaching in acid soils, inhibition of transpiration (high humidity, dry soil, heat)	Pre-mature dropping of buds and blossoms, bending of tips, brown spotting (apples, celery), blossom end rot in tomatoes	Induced Fe deficiency, also B, Mn, Zn, Competes with Mg and K uptake
Magnesium (Mg)	Involved in photosynthesis, protein synthesis, energy transfer	Relatively mobile = symptoms on older leaves	Mainly mass flow, also root interception (Mg)	Other cations (K, Ca)	Interveinal chlorosis/yellowing, mottling, green veins, orange, red or purple discolouration possible, leaves may curl at margins	Ca or Mn deficiency possible
Sulphur (S)	Chlorophyll production, constituent of some proteins	Relatively low mobility	Mass flow (as SO_4)	Other anions (nitrate, chloride) may be taken up in preference if available at high levels	Similar to N deficiency but first in young tissue: light green to yellowish leaves with lighter-coloured veins	Only in form of SO_2 gas emission near industry

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TRACE ELEMENTS						
NUTRIENT	**MAIN FUNCTION**	**MOBILITY IN PLANT**	**MAIN UPTAKE MECHANISM & (UPTAKE FORM)**	**UPTAKE INTERFERENCE OR PROBLEMS**	**DEFICIENCY SYMPTOMS**	**EXCESS SYMPTOMS**
Boron - B	Carbohydrate, starch and sugar metabolism, needed for flowering and pollination, critical component within young growing points (meristematic tissue)	Immobile, moves only with transpiration = symptoms appear on younger plant parts	Mass flow (as BO_4)	High pH Inhibition of transpiration reduces uptake (high humidity, dry soil, heat)	Black/brown heart in leafy plants, cracking and deformation of roots or stalks (corky tissue), hollow stems, die back of twigs, dead buds, poor flowering, fruit set	Narrow margin between sufficiency and toxicity – necrotic spots with yellow margin, may be induced by salinity
Copper - Cu	Constituent of proteins, energy transfer, N fixation in legumes	Relatively low = symptoms most obvious in younger leaves	Mass flow (Cu)	High pH, high Mn levels or other trace metals	Plants look bleached and stunted, tip burn in cereals, dieback of leaves in vegetables, die back of twigs in citrus, mottled leaves	Fe deficiency
Iron (Fe)	Required for photosynthesis, respiration and chlorophyll production	Immobile = symptoms on younger leaves first	Mass flow, diffusion, some root interception (Fe)	High pH (>7), high Ca level, concentration, high Mn levels or other trace metals, esp. Cu	Interveinal chlorosis, leaves become whitish, veins remain green, could be confused with Mg deficiency	Can look like P deficiency

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TRACE ELEMENTS [CONT.]						
NUTRIENT	MAIN FUNCTION	MOBILITY IN PLANT	MAIN UPTAKE MECHANISM & (UPTAKE FORM)	UPTAKE INTERFERENCE OR PROBLEMS	DEFICIENCY SYMPTOMS	EXCESS SYMPTOMS
Manganese (Mn)	Regulation of carbohydrate metabolism and energy transfer	Medium mobility = symptoms appear over entire plant	Mass flow, some root interception (MnO)	High pH	Chlorosis, may display lots of small, black/brown spots	Bark substrates may contain excess Mn, spotting or necrosis along leaf margins, leaves roll up
Molybdenum (Mo)	Essential for N assimilation, important in legumes for rhizobia function	Low mobility = symptoms appear first on young leaves	Mass flow, some root interception	Low pH	Legumes show N-deficiency symptoms, brassicas produce long, narrow, deformed leaves, also typical – chlorosis and upward curling of leaf margin	Chlorotic young leaves, purple in tomatoes, stunted growth, thick leaves, moribund buds
Zinc (Zn)	Carbohydrate metabolism and enzyme activation (similar to Mn)	Reasonably mobile = symptoms appear particularly in older leaves	Mass flow, diffusion, root interception	High pH, high Mn levels or other trace metals	Interveinal chlorosis, stunted, stiff, 'bleached appearance, rosetting in fruit trees (bare twigs with leaf clusters at the end), tip burn in cereals	Similar to Fe and Mn deficiency

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Appendix 2: How do nutrients get from the soil into the plant?

STEP 1 – MOVEMENT OF NUTRIENTS TO THE ROOT SURFACE

Nutrients can reach plant roots via:

- Mass flow – upward water flow through the plant from roots to leaves
- Diffusion – movement from areas of higher concentration to areas of lower concentration
- Root interception – encountering nutrients as the roots grow through the soil.

Mass flow

Mass flow describes the movement of nutrients dissolved in water. Transpiration of water out of the leaf stomata creates a hydraulic 'pull' (pressure gradient). Plants replenish lost water via a continuous column of water moving upwards through the xylem from the roots through to the leaves. Nutrients in the soil solution move along the pressure gradient and can enter the roots dissolved in water. Calcium and boron are only able to move within the plant (upwards, via the xylem) in response to transpiration, independently of how they are entering the plant. Transpiration is inhibited by dry conditions and waterlogging, but also very high humidity (fog, rain) – because there is no pressure gradient into the plant. Wind can improve the pressure gradient. Healthy foliage, a well-developed, healthy root system and a balanced root/shoot ratio are important for a high-pressure gradient.

Diffusion

If a plant is taking up a nutrient, its concentration in the immediate root zone is lowered compared to the soil further away from the root. This means nutrient uptake creates a concentration gradient. Nutrient in the soil will slowly move towards the depleted root zone area to even out the distribution (create an equilibrium). This process of nutrient movement along a concentration gradient is called diffusion. The denser a well-developed, healthy root system, the greater the concentration gradient it can create.

Root interception

As roots grow through the soil, they can intercept nutrients, these can then be taken up by the plant. Most phosphorus (and some calcium gets to the root system this way). It is important to ensure even spread of these nutrients through the soil in the plant root zone and that plants have well-developed, healthy root systems. The roots do not grow towards the nutrients, they happen upon them as they grow.

Table 6 provides an overview of the mobility of nutrients within the soil while Table 7 indicates nutrient transport mechanisms in the soil to the root surface and nutrient mobility in the plant.

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Table 6: Nutrient mobility in the soil

TITLE	SUMMARY	LINK
NH4+	K (potassium, can be leached in sandy soils)	N (nitrate)
P (phosphorus)		S (sulphur)
		B (boron)

Table 7: Macronutrient transport in soils and mobility within plants*

TITLE	SUMMARY	LINK
N	Mass flow	High, plant can actively relocate N
P	Diffusion (very slow) / root interception	High, plant can actively relocate P
K	Diffusion (some mass flow)	Moderate, plant can actively relocate K
Ca	Root interception (some mass flow)	No relocation, moves with water only, no active transport
Mg	Mass flow (some root interception)	Moderate, plant can actively relocate Mg
S	Mass flow	Low, relocation is limited

*For further information see SWICP (2016) - factsheet ‘Nutrient element functions in vegetable crops;’ link in Resources and References.

STEP 2 - MOVEMENT OF NUTRIENTS INTO THE PLANT

Nutrient ions or molecules must be in the soil solution to enable uptake by plants. The ‘move’ from the soil solution to the vascular centre (plumbing) of plant roots occurs by passing through at least one cell membrane (skin). The movement across membranes in roots can be via active or passive transport mechanisms. The highest nutrient uptake occurs in the ‘apical zone’ of the root, the root tip.

- Passive nutrient uptake across cell membranes occurs via diffusion (concentration gradient between the outside and inside of the cell), using either a ‘carrier’ or moving in solution through pores (holes in the cell membrane, that open and close under multiple influences from inside the cell).
- Active transport of nutrients across membranes into roots occurs against a concentration gradient. It requires energy to ‘pump’ ions into the cell. Active transport allows for selective ion uptake. Competition between ions occurs during active transport. The best known and complex competition occurs between cations (e.g., Ca2+ does not compete with K+, K+ competes with Mg2+, Na+ competes with K+, NH4+ competes with K+ but not the reverse). Soil pH influences cation competition but can also affect ion synergism. In saline soils, Cl- can affect N nutrition by reducing NO3- uptake.

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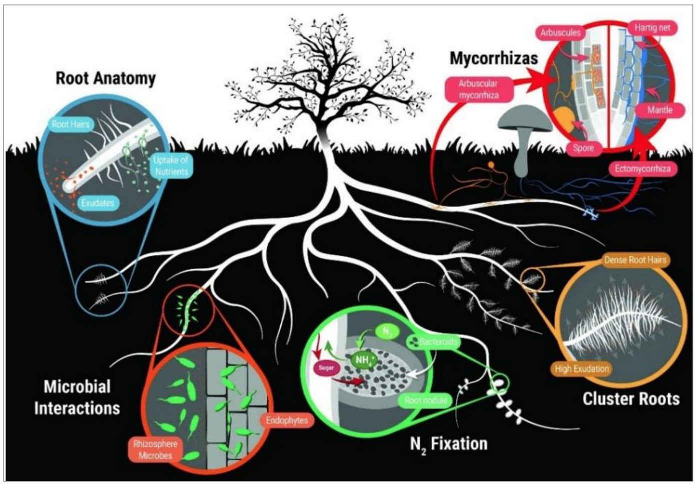

Figure 3: Different plant nutrient acquisition strategies[2]

Plants often face nutrient shortages. Although plants do not move around, they utilise many sophisticated mechanisms (see Figure 3) to acquire enough of the nutrients required for proper growth, development and reproduction. These mechanisms include changes in the developmental program and root structure to better “mine” the soil for limiting nutrients, induction of high affinity transport systems and the establishment of symbioses (e.g., with N-fixing bacteria and with e.g., mycorrhizal associations) that facilitate nutrient uptake into the roots. Together, these mechanisms allow plants to maximise their nutrient acquisition abilities while protecting against the accumulation of excess nutrients in the soil solution, which can be toxic to the plant.

STEP 3 - TRANSPORT WITHIN PLANTS

Nutrients, carbohydrates and other molecules are transported throughout plants in the plant’s vascular system (see Figure 4). It comprises a group of conducting tissues and associated supportive fibers. Xylem tissue transports water and dissolved minerals to the leaves; phloem tissue conducts more complex organic molecules (food), especially carbohydrates, from the leaves to all parts of the plant.

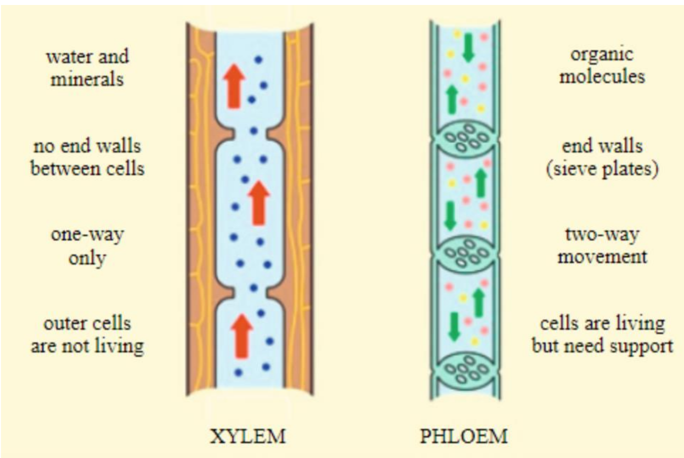

Figure 4: Illustration of xylem and phloem, the transport system within plants[3]

[2] Nutrient uptake from soils. https://www.asps.org.au/wp-content/uploads/Chapter-4-for-PDF-.pdf
[3] https://www.chegg.com/learn/biology/introduction-to-biology/location-of-vascular-tissue-system-in-plant

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Appendix 3: Nutrient interactions

Many scientists have tried to clarify the complicated relationships between nutrients. Some of these relationships are straight forward but, most are not. A few examples from agricultural laboratory research and field-based experiments have shown the below relationships.

Antagonistic nutrients

A nutrient that is at excessive levels in the soil or soil solution can affect the uptake of other nutrients via ion competition. Table 8 shows which nutrients can affect others, if used excessively.

Table 8: Nutrient interactions – effect of excess elements

EXCESS	REDUCED UPTAKE DUE TO EXCESS OF NUTRIENTS
K	Mg, Ca
Ca & Mg	K
Ca	Fe
Na	K, (Ca, Mg)
NH4	all cations
P	Zn, Fe, Mn, Cu
N	S, Cu / P, K, Fe, Ca, Mg Fe, Mn, Zn
S	Se
Mo	Cu
Cl	NO3
Zn	Mn
In principle all trace metals compete	

Synergistic nutrients

Example of synergism where the optimum availability of one nutrient generally support uptake of others are included in Table 9.

Table 9: Nutrient interactions – synergistic effects

OPTIMUM	ENSURES GOOD UPTAKE OF
N	K also P, Mg, Fe, Mn and Zn
Cu & B	N
Mo	P, N utilisation (in plant)
Ca & Zn	P, K
S	Mn, Zn
Mn	Cu

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Nutrient fixing

Nutrients can become unavailable when added as fertiliser to soils. This is called nutrient fixing. Nutrient fixing can be a biological or chemical process. Fixed nutrients are not available for uptake but can be made available via chemical or microbiological reactions.

Phosphorus can be fixed via freely available calcium in the soil solution, typically in soils with pH > 7 (alkaline soils). Phosphorus can be fixed via available iron and aluminium in the soil solution, typically in soils with pH < 6 (acidic soils).

Nitrogen can be fixed when microbes absorb it to build their body mass. This typically occurs when the carbon to nitrogen (C:N) ratio is high i.e. there is a large amount of carbon in the organic matter they are using as a nutrient source, compared to nitrogen. Once the C:N ration exceed 20:1, nitrogen fixing can be expected.

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Appendix 4: pH and liming

Soil pH measured in a calcium chloride solution is the standard method of measuring soil pH in all states other than Queensland. Results are expressed as pH (CaCl2).

For soil pH measured in water, distilled water is used instead of calcium chloride. Results are expressed as pH(w).

The pH (CaCl2) test is the more accurate of the two pH tests, as it reflects what the plants experiences in the soil. The values of pH (CaCl2) are normally lower than pH(w) by 0.5 to 0.9. A useful, but not consistently accurate conversion is to subtract 0.8 from the pH(w) to obtain a pH (CaCl2) value. The difference between the methods can be significant when interpreting results and it is important to know which method has been used, especially if pH figures derived some years apart are being compared to assess any pH fluctuations. In saline spoils, the difference between the two pH values is very small.

Adjusting the pH of acid soils via liming has benefits:

- Plants develop healthier roots because they are exposed to less toxic aluminium; aluminium level increase exponentially once the pH drop below pH5.5. Good root growth means good nutrient and water uptake.
- Lime is a source of calcium (as well as magnesium if dolomite is used). Even though to calcium is not immediately available to crop, lime or dolomite provide a slow-release source.
- Nutrient availability is improved by a pH of 6-6.5, apart from that of trace metals; these may have to be applied via foliar nutrients based on plant monitoring.
- Increased proportion of calcium in the cation exchange capacity (CEC).
- Nodulation of legumes is enhanced, which improves nitrogen fixation, which can be important for rotational crops and legume cover crops.
- Optimal pH improves microbial activity in many soils, thus improving the benefits from good soil microbiology.
- Some soil borne diseases may be less damaging at a neutral pH.

Liming materials are:

- Calcium carbonate ($CaCO_3$)
- Calcium hydroxide [$Ca(OH)_2$]
- Calcium oxide (CaO)
- Magnesium carbonate ($MgCO_3$) called dolomitic lime or dolomite and used when the soil is low in magnesium.

Pure calcium carbonate is used as the standard for liming materials and is assigned a rating of 100%. This rating is also known as the “calcium carbonate equivalent” or” “neutralising value” (NV). All other liming materials are rated in relationship to pure calcium carbonate.

The higher the NV and finer the liming material, the faster the pH will change. Dolomitic limes are slightly more efficient in neutralising soil acidity and may have NV values greater than 100, depending on purity.

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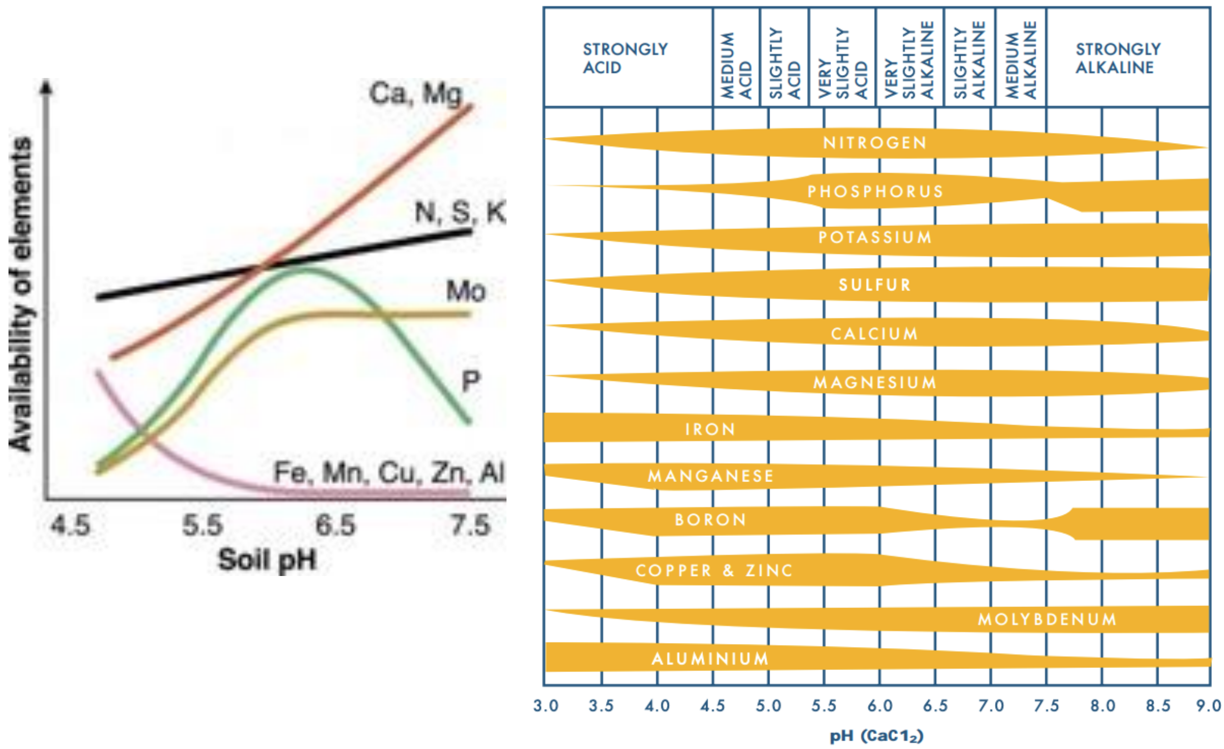

Figure 5: Effect of soil pH and nutrient availability

The graphs in Figure 5 illustrate the relationship between soil pH (CaCl2) and nutrient availability: https://www.agric.wa.gov.au/soil-acidity/effects-soil-acidity) and https://www.dpi.nsw.gov.au/__data/assets/pdf_file/0003/167187/soil-ph.pdf

Determining lime requirement

More lime is required to raise the soil pH in clays than in sands, so it is important to know the soil texture. It is recommended that lime quantity applied at any one time should aim to not raise the soil pH by more than 1 unit. This is particularly important on sands and sandy loams as over-liming may induce or worsen trace element deficiencies.

If more lime is required on these soil types to raise the soil pH to or above 5.5 (CaCl2) then application will need to be split. Apply an application now and another application in about 3–4 years' time.

Lime application rates on soils with very low organic carbon levels (less than 0.5 % for sand; less than 0.7 % for sandy loam and less than 1.2 % for clays) need to be adjusted by cutting the lime application rate by 25 % from calculated total required.

The below lime requirement calculation is based on a pure lime or an NV of 100%. If the NV of the material to be used is less than this, then higher rates of lime NV (adjusted) can be used.

Lime requirement (t/ha) = (target pH – current pH) x soil texture factor.

Soil texture factors:

- Loam to clay loam: 4
- Sandy loam: 3
- Sand: 2

For example: to raise a sandy loam soil of pH 4.8 (CaCl2) to pH 5.5 (CaCl2), (5.5 – 4.8) x 3 = 2.1 tonnes of lime per hectare is required.

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Appendix 5: Fertiliser nutrient composition and concentration

In Australia, mineral fertilisers are labelled with the percentage (%) of N:P:K (and other nutrients) they contain (= fertiliser grade). The grade is always listed on the packaging or data sheet and always in the order of nitrogen, phosphorous, and potassium, then sulphur, magnesium, calcium. Trace element concentrations are added where required. The percentage of each nutrient is expressed as a proportion of product weight (w/w %), e.g., 18:10:16:5 shows the ratio of N:P:K, or 18 kg N, 10 kg P and 16.6 kg K in 100 kg of product.

Australia has a National Code of Practice for Fertilizer Description & Labelling, prepared by Fertilizer Australia (2018)[4].

In Europe and the USA, mineral fertilisers are labelled to show the concentration of nitrogen (N), phosphorus (P) and potassium (K). The P concentration is reported as P_2O_5 and the K concentration as K2O. Fertilisers do not actually contain P_2O_5 or K_2O, but the system is a conventional shorthand for the amount of the phosphorus (P) or potassium (K) in a fertiliser.

- To convert P_2O_5 to elemental P divide the P_2O_5 concentration (%) by 2.29
- To convert P to P_2O_5 multiply by 2.29
- To convert K_2O to K divide by 1.21
- To convert K to K_2O. multiply by 1.21.

Refer to Table **10** for further conversions between fertilisers and elements.

For liquid products, the analysis for each nutrient is expressed as a proportion of each nutrient's weight by volume (w/v %), e.g. 3 kg per 100 liters of product (3% w/v). Product density (g/cm3) can be used to convert w/v % to weight by weight proportions (w/w %).

Conversion calculations[5]:

w/v% $$\frac{\text{weight}}{\text{volume}}\% = \frac{\text{weight of solute (kg)}}{\text{volume of solution (L)}} \times 100$$

w/w% $$\frac{\text{weight}}{\text{weight}}\% = \frac{\text{weight of solute (kg)}}{\text{weight of solution (kg)}} \times 100$$

v/v% $$\frac{\text{volume}}{\text{volume}}\% = \frac{\text{volume of solute (L)}}{\text{volume of solution (L)}} \times 100$$

w/v% to w/w% $$\frac{\text{weight}}{\text{weight}}\% = \frac{\text{weight of solute (kg)}}{\text{volume of solution (L)}} \times 100 \times \text{product density (g/cm}^3\text{)}$$

Solute – the thing you're dissolving, in this case the undissolved raw product

Solvent – the liquid you're dissolving it in, usually water

Solution – the final combination of the solute and solvent

[4] https://fertilizer.org.au/Fertilizer-Issues/Labelling-And-Description
[5] for a conversion calculator and source of the formulae see: https://www.physiologyweb.com/calculators/percent_solutions_calculator.html

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Table 10: Conversion guide for fertilisers

GIVEN	FACTOR	WANTED
Nitrogen		
N	2.17	Urea
Urea	0.46	N
N	1.22	NH_3
NH3	0.82	N
N	8.33	MAP
MAP	0.12	N
N	5.56	DAP
DAP	0.18	N
N	2.90	AN
AN	0.35	N
N	4.76	AS
AS	0.21	N
N	7.21	KNO_3
KNO_3	0.14	N
N	6.07	$NaNO_3$
$NaNO_3$	0.16	N
Phosphorus		
P_2O_5	5.00	SSP
SSP	0.20	P_2O_5
P_2O_5	2.17	TSP
TSP	0.46	P_2O_5
P_2O_5	2.17	DAP
DAP	0.46	P_2O_5
P_2O_5	1.92	MAP
MAP	0.52	P_2O_5
P_2O_5	1.92	MKP
MKP	0.52	P_2O_5
Potash / Potassium		
K_2O	0.83	K
K	1.20	K_2O
K_2O	1.67	KCl
KCl	0.60	K_2O
Polysulphate	0.14	K_2O
K_2O	7.14	Polysulphate
Polysulphate	0.12	K
K	8.62	Polysulphate
K_2O	1.85	K_2SO_4
K_2SO_4	0.54	K_2O
KNO_3	0.47	K_2O
K_2O	2.15	KNO_3
MKP	0.34	K_2O
K_2O	2.94	MKP

AREA CONVERSION		
kg/ha	0.892	lb/ac
lb/ac	1.121	kg/ha
Other		
Polysulphate	0.06	MgO
MgO	16.67	Polysulphate
Polysolphate	0.036	Mg
Mg	27.78	Polysulphate
Polysulphate	0.17	CaO
CaO	5.88	Polysulphate
Polysulphate	0.122	Ca
Ca	8.2	Polysulphate
Sulphur		
SO_3	0.40	S
S	2.50	SO_3
SO_4	0.33	S
S	3.00	SO_4
SO_3	2.08	Polysulphate
Polysulphate	0.48	SO_3
S	5.21	Polysulphate
Polysulphate	0.19	S
SO_3	1.67	AS
AS	0.60	SO_3
SO_3	3.33	SSP
SSP	0.30	SO_3
Oxide Conversions		
K_2O	0.83	K
K	1.20	K_2O
P_2O_5	0.44	P
P	2.29	P_2O_5
SO_3	0.40	S
S	2.50	SO_3
SO_4	0.33	S
S	3.00	SO_4
Mg	1.658	MgO
MgO	0.603	Mg
Ca	1.399	CaO
CaO	0.715	Ca
Na_2O	0.742	Na
Na	1.348	Na_2O
Na	2.70	NaCl
NaCl	0.37	Na
Na_2O	2.00	NaCl
NaCl	0.50	Na_2O
B	3.18	B_2O_3
B_2O_3	0.31	B
Zn	1.24	ZnO
ZnO	0.81	Zn

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Appendix 6: Nutrient Stewardship

The International Plant Nutrition Institute's 4R Plant Nutrition Stewardship provides a framework to achieve cropping system goals, such as increased production, increased farmer profitability, enhanced environmental protection and improved sustainability. The principles have been adopted by Fertilizer Australia, the industry association representing manufacturers, importers, and distributors of fertiliser in Australia, and the associated services, in their Fertcare Program. The Program currently focusses on broadacre crops and intensive grazing industries. Still, the 4R principles apply to horticulture:

1. **Right fertiliser source** at the (2) **Right rate**, at the (3) **Right time** and in the (4) **Right place (image – Nutrient Stewardship).**

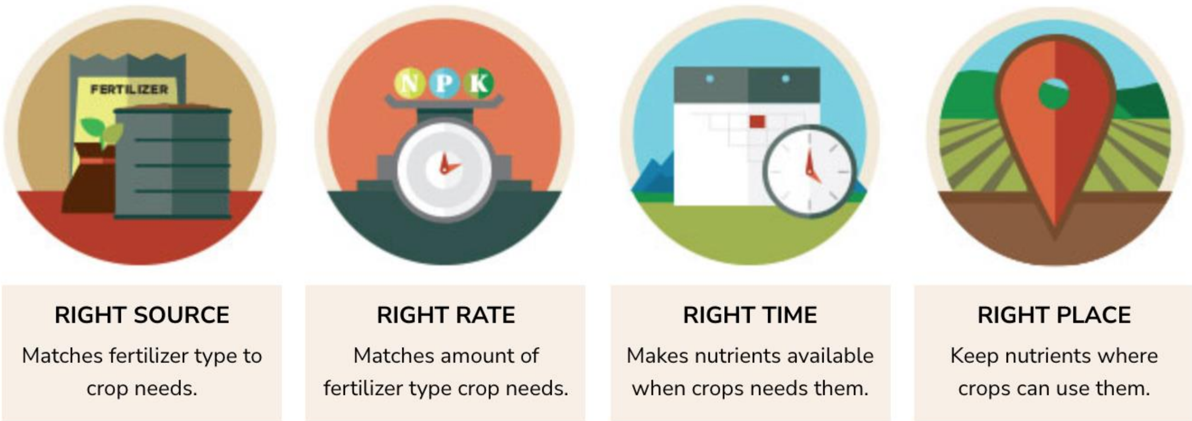
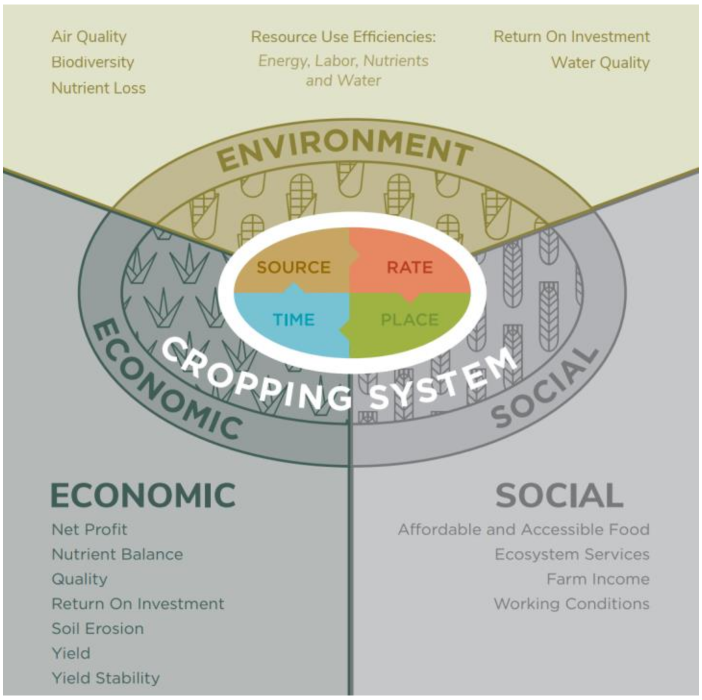


Figure 6: The 4R principle of fertiliser use



Vegetable growers can use the EnviroVeg or Freshcare Environmental program to demonstrate good nutrient stewardship to their customers and consumers.

Figure 7: The 4R principle in context

(Source of Figure 6and Figure 7: Nutrient Stewardship / International Plant Nutrition Institute - https://nutrientstewardship.org/4r-pocket-guide/)

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Right source (what)

Choose the right fertiliser source for a specific set of conditions, while also considering rate, time and place of application.

Supply nutrients in plant-available forms

- The nutrient applied is plant-available, or is in a form that converts in a timely manner into a plant-available form in the soil.

Ensure the source suits the receiving soil's physical, biological and chemical properties

- For instance, avoid nitrate application to waterlogged soils, or surface applications of urea to high pH soils and/or in dry or cold conditions.

Consider synergisms or antagonisms among nutrient elements and sources

- Examples include the phosphorous-zinc (P-Zn) interaction, nitrogen (N) increasing phosphorous (P) availability, fertiliser complementing organic amendments, not adding nutrients already available in abundance.

Check fertiliser blend compatibility

- Certain combinations of sources attract moisture when mixed, limiting uniformity of application of the blended material; granule size should be similar to avoid product segregation. Composite or slow release fertilisers or liquids may be a better choice.

Consider benefits and sensitivities of supplementary elements

- Most nutrients have an accompanying ion that may be beneficial, neutral, or detrimental to the crop or soil. For example, the chloride (Cl-) accompanying potassium (K+) in muriate of potash (MOP) can be beneficial to sweet corn or tomatoes but can be detrimental to the quality of some vegetables and fruits. It should not be used on saline soil or if irrigation water is saline.
- Some sources of P fertiliser may contain plant-available Calcium (Ca) and sulphur (S) and small amounts of magnesium (Mg) and micronutrients.

Control effects of elements that are not nutrients

- For example, natural deposits of some phosphate rock contain trace elements such as cadmium that can be toxic to animals or people. The level of addition of these elements should be kept within acceptable thresholds and regulations.

Right rate (how much)

Work out the right rate for a specific set of conditions, while also considering source, time and place of application.

Assess plant nutrient demand.

- If all growing conditions are as required and the soil is in good physical, biological and chemical balance, yield is related to the quantity and balance of nutrients taken up by the crop until maturity. The selection of a meaningful yield target that is attainable with optimal growing conditions, crop, irrigation and nutrient management, and the given variability within paddocks and from season to season provides important guidance on the estimation of total crop nutrient demand.

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Use adequate methods to assess soil nutrient needs (i.e., know what to put where)

- Practices used may include soil and plant analysis, response experiments, nutrient omission plots, use of precision agriculture tools such as assessing and addressing spatial variability of soil conditions (e.g. pH, nutrients, salinity, drainage).

Include all nutrient sources available to the crop in the nutrient budget

- For most farms, this assessment includes the quantity and plant availability of nutrients in soil, organic amendments if used (composted manure, composts, biosolids), crop residues, atmospheric deposition, and irrigation water, as well as mineral fertilisers.

Predict fertiliser nutrient use efficiency

- Some inefficiencies are unavoidable, so to meet plant demand, this must be considered in the nutrient budget, e.g., P-fixing capacity of the soil, potential N-fixing, volatilisation and/or denitrification.

Consider soil resource impacts

- If the removal of nutrients from a cropping system (via harvested crop) exceeds nutrient inputs from all sources, soil fertility declines over time.

Consider rate-specific economics

- For nutrients unlikely to be retained in the soil (potentially lost via leaching, or to the atmosphere e.g. nitrogen or boron), the most economic rate of application is where an additional unit of nutrient applied to a crop is equal in value to the increase in crop yield it generates (law of diminishing returns).
- For nutrients retained in the soil, their value to future crops should be considered.
- Assess probabilities of predicting economically optimum rates and the effect on net returns (gross margin loss) arising from errors in prediction.

Right time (when)

Choose the right time for a specific set of production conditions, while also considering source, rate and place of application.

Assess timing of plant uptake

- Nutrients should be applied to match the seasonal crop nutrient demand which depends, for instance, on planting date, plant growth characteristics, or sensitivity to deficiencies at particular growth stages.
- Consider the capacity of soil reserves to be available at times of high demand. Potassium for instance may be at adequate levels in the soil; however, at times of very high demand during rapid crop growth, flowering and fruit development, diffusion from soil reserves may be inadequate; a foliar application may be a good way to address the issue.

Assess dynamics of soil nutrient supply

- Mineralisation of soil organic matter supplies a large quantity of some nutrients, especially nitrogen during warm weather. If the crop's uptake need precedes its release, deficiencies may limit productivity. A foliar application may be a good way to address the issue rather than soil applied fertiliser, given that a release of the nutrient is still expected.

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Consider the dynamics of soil nutrient loss

- In light soils or surface run-off (erosion), **leaching losses** of, for example, N, S, boron (B) and also K, or any nutrient on or within the soil **surface occur during times when rainfall exceeds the water holding capacity or infiltration rate of the soil**. Therefore:
  - Avoid nutrient applications prior to heavy rain.
  - Ensure good erosion control measures are in place.
  - Use cover crop(s) and deep rooted 'catch crops' to use nutrients remaining in the soil after harvest and thus prevent losses.

Evaluate logistics of field operations

- For example, multiple applications of nutrients (e.g., foliar applications) may or may not be compatible with those of crop protection products.
- **Nutrient applications should not delay time-sensitive operations** such as planting or crop protection, however nutrients still must be available within a certain window to avoid setbacks in crop growth.

Right place (where)

Choosing the right place means strategically positioning nutrient supplies in the rootzone so that plants can access them. Proper placement allows crops to realise their potential yield, within the given environmental and crop management conditions.

The technologies for 'right place' are still evolving. Numerous factors can affect proper fertiliser placement in the rootzone, including but not limited to, the following:

- Plant genetics
- Plant spacing / bed configuration
- Placement technologies
- Crop rotation or intercropping
- Tillage practices
- Weather variability
- Irrigation systems and soil water management.

There is still much to learn about what constitutes "right" in 'right place' and how well it can be predicted when management decisions need to be made. The main principles that define 'right place' for a specific nutrient application are to consider source, rate and time of application.

Consider where plant roots are growing

- Nutrients need to be placed where they can be taken up by growing roots when needed.
- Consider soil chemical reactions.
- Concentrating easily fixed nutrients like P in bands or smaller soil volumes close to roots can improve availability.

Suit the goals of the tillage system

- Subsurface placement techniques that maintain crop residue cover on the soil can help conserve nutrients and water.

Manage spatial variability

- Assess soil differences within and among paddocks in crop productivity, soil nutrient supply capacity, and vulnerability to nutrient loss.

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Appendix 7: Resources

Table 11 : Relevant resources for good nutrition management (source: www.soilwealth.com.au)

TITLE	SUMMARY	LINK
Labile carbon Fact sheet, September 2018	This fact sheet outlines why labile carbon is used as a leading indicator of soil health and how you can undertake your own field test.	https://www.soilwealth.com.au/resources/fact-sheets/soil-nutrition-and-compost/labile-carbon/
Getting soil pH right – Lime quality and application rates Fact sheet, January 2019	This fact sheet describes the causes and effects of soil acidification and explains how liming increases soil pH differently depending on your soil type, as well as ways to manage paddock variability.	https://www.soilwealth.com.au/resources/fact-sheets/soil-nutrition-and-compost/getting-soil-ph-right-lime-quality-and-application-rates/
Managing salinity in vegetable crops Fact sheet, August 2019	Read this fact sheet to find out more about good salinity management practices on farm, salinity thresholds for vegetables and how salinity can be identified and measured.	https://www.soilwealth.com.au/resources/fact-sheets/soil-nutrition-and-compost/managing-salinity-in-vegetable-crops/
Managing salinity in vegetable crops Webinar recording, November 2019	Industry experts share their knowledge on good salinity management practices on-farm in this interactive webinar.	https://www.soilwealth.com.au/resources/webinar-recordings/managing-salinity-in-vegetable-crops/
Soil phosphorus – The basics Fact sheet, September 2019	Read about the common characteristics of soil phosphorus, its availability for uptake by plants and practical management tips and tools in line with the 4R principles.	https://www.soilwealth.com.au/resources/fact-sheets/soil-nutrition-and-compost/soil-phosphorus-the-basics/
Nitrate field test Fact sheet, January 2020	This simple and easy to use guide outlines how a quick nitrate test can be conducted in the field.	https://www.soilwealth.com.au/resources/ fact-sheets/soil-nutrition-and-compost/ nitrate-field-test/page8image55468096page8image55467904
Taking soil samples Fact sheet, January 2020	This fact sheet provides guidance on how to take soil samples correctly.	https://www.soilwealth.com.au/resources/ fact-sheets/taking-soil-samples/page8image55464640page8image55464064
Plant analysis for vegetable crops: A practical guide to sampling, analysis and interpretation Articles and publications, February 2020	This guide covers laboratory-based plant nutrient analyses, specifically dry matter analysis and sap analysis.	https://www.soilwealth.com.au/resources/ articles-and-publications/plant-analysis- for-vegetable-crops-a-practical-guide-to- sampling-analysis-and-interpretation/page8image55419328page8image55421824page8image55417600page8image55413760
Managing sodicity in vegetable crops Fact sheet, May 2020	This fact sheet explains what sodicity is, how to identify sodicity in soils, its impact on soil and crops, as well as management options.	https://www.soilwealth.com.au/resources/ fact-sheets/soil-nutrition-and-compost/ managing-sodicity-in-vegetable-crops/page8image55543872page8image55546752+A9

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TITLE	SUMMARY	LINK
Making the Most of your Nitrogen Fact sheet, 2017	This fact sheet provides information on the need for nitrogen application, how it can improve vegetables farming systems, and the correct applications to administer to increase production and reduce leaching and run-off.	https://www.soilwealth.com.au/imagesDB/news/SW_MakingthemostofNitrogen_FINAL.pdf
2020 Vegetable Crop Nutrition Masterclass kicks off Articles, August 2020	Over two days, 36 vegetable growers and agronomists across Australia are taking part in an interactive event which will build on their existing knowledge and help to improve their crop nutrition programs on-farm, particularly during difficult growing conditions.	https://www.soilwealth.com.au/resources/articles-and-publications/2020-vegetable-crop-nutrition-masterclass-kicks-off-online/
A breezy video update from Koo Wee Rup Video, October 2021	Soil Wealth ICP team member Carl Larsen braved the windy weather at our Koo Wee Rup demonstration site in Victoria to bring growers a short update on how things were progressing at the site.	https://www.soilwealth.com.au/resources/videos-and-apps/a-breezy-video-update-from-koo-wee-rup/
Taking soil samples? We'll show you how it's done at Koo Wee Rup Video, November 2021	While taking soil samples at our Koo Wee Rup demonstration site in Victoria recently, Soil Wealth ICP team member Carl Larsen recorded a short video about the key things to keep in mind to ensure you collect a quality soil sample for testing.	https://www.soilwealth.com.au/resources/videos-and-apps/takingsoil-samples-we-show-you-how-its-done-at-koo-wee-rup/
Interest is growing around biochar as both a soil amendment and to increase carbon sequestration to soil. Webinar recording, November 2021	Information on biochar as both a soil amendment and to increase carbon sequestration to soil.	https://www.soilwealth.com.au/resources/fact-sheets/soil-nutrition-and-compost/biochar-what-is-its-potential-for-vegetable-production/
Compost calculator: knowing the value of organic amendments in your vegetable nutrition program in Victoria Webinar recording, February 2021	Information from a current project delivered by Queensland University of Technology in collaboration with La Trobe University to provide growers and industry service providers with an effective decision support tool to integrate organic amendments into farm nutrient budgets.	https://www.soilwealth.com.au/resources/webinar-recordings/compost-calculator-knowing-the-value-of-organic-amendments-in-your-vegetable-nutrition-program-in-victoria/
Organic soil amendments Global scan and review, December 2020	This 2018 global scan and review, updated in December 2020, covers what organic soil amendments are, why and how to use them, and its effect on soils and crops.	https://www.soilwealth.com.au/resources/global-scan-and-reviews/organic-soil-amendments/
South Australian grower compost trial Case study, September 2019	Two demonstration trial sites on the Northern Adelaide Plains showcase how compost could be used to improve soil health.	https://www.soilwealth.com.au/resources/case-studies/south-australian-grower-compost-trial/
Recycled organics for vegetable growers Fact sheet, July 2019	This fact sheet outlines the benefits and risks of using recycled organics on-farm, as well as typical application rates, costs, application methods and nutrient analysis.	https://www.soilwealth.com.au/resources/fact-sheets/soil-nutrition-and-compost/recycled-organics-for-vegetable-growers/
Compost trial, Virginia, SA Podcast, April 2019	The Soil Wealth and ICP team follow the implementation of a compost trial for vegetable growers in Virginia, South Australia.	https://www.soilwealth.com.au/resources/podcasts/compost-trial-virginia-sa/
Recycled organics (compost) in vegetable production Webinar recording, March 2019	This webinar recording discusses the value of recycled organics and explains how compost can be successfully integrated into vegetable farming in Australia.	https://www.soilwealth.com.au/resources/webinar-recordings/recycled-organics-compost-in-vegetable-production/

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Developing a fertiliser program for vegetable crops (webinar recording) Podcast, February 2019	This podcast of a webinar recording provides evidence-based knowledge to make good decisions on site-specific nutrient management of vegetable crops.	https://www.soilwealth.com.au/resources/podcasts/developing-a-fertiliser-program-for-vegetable-crops-webinar-recording/
The Carbon Series part 1: Carbon farming and its relevance to vegetable growers Global scan & review, January 2022	This four-part Carbon Series from the Soil Wealth ICP project breaks down the practicalities of carbon farming for vegetable growers and looks more closely at soil carbon management. Part 1 provides an overview of carbon farming and its relevance to Australian vegetable growers.	https://www.soilwealth.com.au/resources/global-scan-and-reviews/the-carbon-series-part-1-carbon-farming-and-its-relevance-to-australian-vegetable-growers/
The Carbon Series part 2: Soil carbon and carbon sequestration Global scan & review, January 2022	This four-part Carbon Series from the Soil Wealth ICP project breaks down the practicalities of carbon farming for vegetable growers and looks more closely at soil carbon management. Part 2 delves into soil carbon and carbon sequestration.	https://www.soilwealth.com.au/resources/global-scan-and-reviews/the-carbon-series-part-2-soil-carbon-and-carbon-sequestration/
The Carbon Series part 3: Carbon emissions in vegetable production Global scan & review, January 2022	This four-part Carbon Series from the Soil Wealth ICP project breaks down the practicalities of carbon farming for vegetable growers and looks more closely at soil carbon management. Part 3 discusses carbon emissions in vegetable production.	https://www.soilwealth.com.au/resources/global-scan-and-reviews/the-carbon-series-part-3-carbon-emissions-in-vegetable-production/
The Carbon Series part 4: Carbon accounting and the Emissions Reduction Fund Global scan & review, January 2022	This four-part Carbon Series from the Soil Wealth ICP project breaks down the practicalities of carbon farming for vegetable growers and looks more closely at soil carbon management. Part 4 takes you through carbon accounting and the Emissions Reduction Fund.	https://www.soilwealth.com.au/resources/global-scan-and-reviews/the-carbon-series-part-4-carbon-accounting-and-the-emissions-reduction-fund/
Carbon management on vegetable farms - emissions, sequestration and beyond Webinar recording, November 2021	Carbon is the main component of soil organic matter and helps give soil its water-retention capacity, its structure, and its fertility. The management of carbon is not only important for soil health and productive vegetable crops but may be also increasingly important in carbon markets and reducing the effects of climate change.	https://www.soilwealth.com.au/resources/webinar-recordings/carbon-management-on-vegetable-farms-emissions-sequestration-and-beyond/
Soil Biology Masterclass 2021: Soil structure Webinar recording, November 2021	Soil Wealth ICP team member Doris Blaesing discusses soil biology and its links to soil structure in vegetable crops.	https://www.soilwealth.com.au/resources/webinar-recordings/soil-biology-master-class-2021-soil-structure-day-1-part-4-of-7/
Soil Biology Masterclass 2021: Soil fumigation - chemical and biological Webinar recording, November 2021	Dr Shane Powell from the Tasmanian Institute of Agriculture joins the Soil Wealth ICP team to share her expertise on soil fumigation and its effects on soil biological communities.	https://www.soilwealth.com.au/resources/webinar-recordings/soil-biology-master-class-2021-soil-fumigation-chemical-and-biological-day-1-part-5-of-7/
Soil Biology Masterclass 2021: Disease suppression Webinar recording, November 2021	Plant pathologist Dr Len Tesoriero joins the Soil Wealth ICP team to present on soil-borne disease suppression in vegetable crops.	https://www.soilwealth.com.au/resources/webinar-recordings/soil-biology-master-class-2021-disease-suppression-day-1-part-6-of-7/
Soil Biology Masterclass 2021: Biological products Webinar recording, November 2021	Soil Wealth ICP team member Pieter van Nieuwenhuyse delves into the use of biological products in Australian vegetable production.	https://www.soilwealth.com.au/resources/webinar-recordings/soil-biology-master-class-2021-biological-products-day-1-part-7-of-7/

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Soil Biology Masterclass (Day 1 recording) Webinar recording, August 2021	Watch this masterclass recording to indulge in the complex world of soil biology and how it relates to healthy and profitable vegetable production. Questions are also discussed and answered throughout this 3.5 h session.	https://www.soilwealth.com.au/resources/webinar-recordings/soil-biology-master-class-2021-day-1-recording/
Soil Biology Masterclass 2021: Panel discussion on soil biology testing (Day 2) Webinar recording, November 2021	Day 2 of the Soil Biology Master Class featured a panel discussion on soil biology testing with Kelvin Montagu.	https://www.soilwealth.com.au/resources/webinar-recordings/soil-biology-master-class-2021-panel-discussion-on-soil-biology-testing-day-2/
Soil Biology Masterclass 2021: Soil biology in vegetable production - basic principles Webinar recording, October 2021	Soil Wealth ICP team member Kelvin Montagu looks at the linkage between key soil functions and soil biology, and the interactions between plant roots and soil biology.	https://www.soilwealth.com.au/resources/webinar-recordings/soil-biology-master-class-2021-introduction-day-1-part-1-of-7/
Soil Biology Masterclass 2021: Nitrogen availability Webinar recording, October 2021	Soil Wealth ICP team members Kelvin Montagu and Marc Hinderager look into nitrogen availability in vegetable crops and its impact on soil biology.	https://www.soilwealth.com.au/resources/webinar-recordings/soil-biology-master-class-2021-nitrogen-availability-day-1-part-3-of-7/
Soil Biology Masterclass 2021: Breakdown of organic matter and agrochemicals in vegetable soil Webinar recording, October 2021	Soil Wealth ICP team members Kelvin Montagu and Marc Hinderager look into breakdown of organic matter, agrochemicals and impact on soil biology.	https://www.soilwealth.com.au/resources/webinar-recordings/soil-biology-master-class-2021-breakdown-of-plant-biomass-and-agrochemicals-day-1-part-2-of-7/
Soil organic matter, biology and mineralisation - The challenges & complexity of estimating mineralisation rates Webinar recording, May 2021	AHR's Marc Hinderager and Soilpack Services' Ian Packer team up to deliver a webinar on soil organic matter, soil biology and the challenges and complexity of estimating mineralisation rates in soils.	https://www.soilwealth.com.au/resources/webinar-recordings/soil-organic-matter-biology-and-mineralisation-the-challenges-complexity-of-estimating-mineralisation-rates/
Boosting mycorrhizal fungi in vegetable crops Case study, April 2021	This case study examines why and how vegetable growers can boost beneficial mycorrhizal fungi in their crops. It also shares the results from a trial which looked at the potential of cover crops, together with commercial mycorrhizal inoculants and reduced soil tillage, to increase the beneficial fungi in vegetable crops.	https://www.soilwealth.com.au/resources/case-studies/boosting-mycorrhizal-fungi-in-vegetable-crops/
How do you know your soil is healthy? Top tips for vegetable growers Fact sheet, December 2020	This fact sheet discusses how a soil health status or soil condition can provide insights into a soil's capacity to fulfil all soil functions. It also outlines how soil organic matter and soil organic carbon can indicate the physical, chemical and biological benefits associated with soil health.	https://www.soilwealth.com.au/resources/fact-sheets/soil-nutrition-and-compost/how-do-you-know-your-soil-is-healthy-top-tips-for-vegetable-growers/
What you need to know about soil microbiology Fact sheet, October 2020	Soil health is closely linked to soil microbiology. This fact sheet outlines information on a broad group of soil microbes including fungi, bacteria and pseudomonas, and explains how different levels, numbers and ratios of these microbes can impact the overall health of your soil and crops.	https://www.soilwealth.com.au/resources/fact-sheets/soil-nutrition-and-compost/what-you-need-to-know-about-soil-microbiology/
Soil biology and biological products: An introduction (30 min listen) Podcast, July 2020	Soil biology is a complex, dynamic and broad field. This podcast will introduce you to the concept of why biology is important to soil fertility and maximising crop production.	https://www.soilwealth.com.au/resources/podcasts/soil-biology-and-biological-products-an-introduction-podcast-30-minute-listen/

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TITLE	SUMMARY	LINK
Cover crops and soil biology in vegetable soils Webinar recording, June 2020	This webinar recording discusses the impacts of cover crops on soil microbial communities.	https://www.soilwealth.com.au/resources/webinar-recordings/cover-crops-and-soil- biology-in-vegetable-soils/
Nitrogen fertiliser price and supply: management options in difficult conditions Webinar recording, March 2022	The commercial nitrogen fertiliser market has been very volatile the past seven months. Supply issues from China, Russia, as well as Europe, have caused shipping issues and shortages for all of Australia. Australia does not manufacture enough nitrogen to supply its own domestic market. Watch this webinar recording to hear from industry experts about best practice nitrogen management options in vegetable production.	https://www.soilwealth.com.au/resources/webinar-recordings/nitrogen-fertiliser-price-and-supply-management-options-in-difficult-conditions/
Cover crop termination guide Posters, February 2022	Make sure your cover crop is terminated before seed set to prevent it becoming a weed.	https://www.soilwealth.com.au/resources/posters/cover-crop-termination-guide/
Nitrogen fertiliser price and supply: A good reason to look at legume cover crops Articles, January 2022	The commercial nitrogen fertiliser market has been very volatile the past seven months. Supply issues from China, Russia, as well as Europe, have caused shipping issues and shortages for all of Australia. Given the price rises and uncertainty of nitrogen fertiliser supply, it's a good time to look at legume cover crops.	https://www.soilwealth.com.au/resources/articles-and-publications/nitrogen-fertiliser-price-and-supply-a-good-reason-to-look-at-legume-cover-crops/
Cover crop herbicide guide Posters, February 2022	Establishing a cover crop can be a great time to get on top of a problem weed without herbicides. See the Cover Crops for Australian Vegetable Growers poster for suggestions for cover crops to suppress weeds through quick establishment and/or dense canopies.	https://www.soilwealth.com.au/resources/posters/cover-crop-herbicide-guide/
Selecting a sorghum cover crop for integrated crop protection Case study, December 2021	Sorghum (Sorghum bicolor), sudangrass (Sorghum sudanense) and their hybrids (S. bicolor X S. sudanense) are popular summer cover crops. They provide excellent protection of the soil against summer storms, are drought and heat tolerant, good at suppressing weeds and recovering nutrients from depth, and can add large amounts of biomass back into the soil. Sorghum species are also an excellent break crop for most vegetable growers and are useful as part of an Integrated Crop Protection (ICP) approach.	https://www.soilwealth.com.au/resources/articles-and-publications/selecting-a-sorghum-cover-crop-for-integrated-crop-protection/
The benefits of cover crops and reduced tillage: Koo Wee Rup Video, November 2021	In this short video update, Soil Wealth ICP team member Carl Larsen explains how practical approaches such as cover crops and reduced tillage is complementing precision agriculture trials at our demonstration site in Koo Wee Rup, Victoria.	https://www.soilwealth.com.au/resources/webinar-recordings/the-benefits-of-cover-crops-and-reduced-tillage-koo-wee-rup/
Uncovering the world of cover crops for vegetable growers Case study, January 2021	This poster provides a strong starting point to help vegetable growers choose a cover crop to suit their farming operation, climate and cover crop objectives. You can find plenty of information on the benefits, growth tolerances, soil conditions, sowing and establishment traits for a range of cover crop species.	https://www.soilwealth.com.au/resources/posters/uncovering-the-world-of-cover-crops-for-veg-growers/
Cover crops – The advantages of Sun hemp Video, July 2020	This video focuses on the advantages of Sunn hemp as a cover crop and provides guidance on sowing, management, and termination.	https://www.soilwealth.com.au/resources/videos-and-apps/cover-crops-the-advantages-of-sunn-hemp/

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Using cover crops to manage mycorrhizal fungi in vegetable crops Webinar recording, July 2020	Dr Kelvin Montagu summarises the potential role of cover crops in managing mycorrhizal fungi in vegetable production.	https://www.soilwealth.com.au/resources/webinar-recordings/using-cover-crops-to- manage-mycorrhizal-fungi-in-vegetable-crops/
Mixed cover crops trial for soil health: Soil First Tasmania demonstration site podcast (14 min listen) Podcast, June 2020	This podcast looks at the value of on-farm trials, and the support given to practice change through grower groups. Two Tasmanian growers also share the challenges and teachings from their on-farm trials.	https://www.soilwealth.com.au/resources/podcasts/mixed-cover-crops-trial-for-soil- health-soil-first-tasmania-demonstration-site-podcast-14-min-listen/
Cover crop trial discussion: East Gippsland Vegetable Innovation Days Video, May 2020	Dr Kelvin Montagu, John Duff (Queensland Department of Agriculture and Fisheries) and Carl Larsen (Soil Wealth ICP) discuss the results of a cover crop trial at the 2020 East Gippsland Vegetable Innovation Days.	https://www.soilwealth.com.au/resources/videos-and-apps/cover-crop-trial-discussion-east-gippsland-vegetable-innovation-days/
Biofumigation cover crops part 1: What variety and when? Webinar recording, December 2019	There are many brassica species and cultivars that can be grown as biofumigants or cover crops. Part 1 of this webinar recording looks at the growth of 17 different biofumigant cover crops across the year in southern Queensland.	https://www.soilwealth.com.au/resources/webinar-recordings/biofumigation-cover-crops-part-1-what-variety-and-when/
Biofumigation cover crops part 2: Pest and diseases and impact on soil-borne diseases Webinar recording, December 2019	Part 2 of this webinar looks at potential pest and disease issues while growing cover crops and the potential impact on soil-borne diseases following incorporation.	https://www.soilwealth.com.au/resources/webinar-recordings/biofumigation-cover-crops-part-2-pest-diseases-impact-on-soilborne-diseases/
Growing Matters #1: Basics of cover cropping with Dr Kelvin Montagu (9 min listen) Podcast, July 2019	Get inspired by this podcast with Dr Kelvin Montagu which provides a good overview on cover cropping, the key benefits for using it on your farm as well as some handy tips and methods for doing it successfully.	https://www.soilwealth.com.au/resources/podcasts/growing-matters-1-basics-of-cover- cropping-with-dr-kelvin-montagu-9-min- listen/
Growing Matters #2: Link between soil wealth and cover cropping with Dr Kelvin Montagu (12 min listen) Podcast, September 2019	Dr Kelvin Montagu explains how cover crops integrate with vegetable production systems and how keeping your soil healthy plays a big role on the wellbeing of your crops.	https://www.soilwealth.com.au/resources/podcasts/growing-matters-2-link-between-soil-wealth-and-cover-cropping-with-dr-kelvin-montagu-12-min-listen/
Cover crops with Harvest Moon Podcast, May 2019	The Soil Wealth ICP team look at how Harvest Moon in Tasmania is using cover crops to protect and improve their precious red soil.	https://www.soilwealth.com.au/resources/podcasts/cover-crops-with-harvest-moon/
Soil moisture the real winner in a hot, dry summer at the Cowra demonstration site, NSW Articles and publications, March 2019	Read this update to learn more about the soil moisture monitoring results for summer 2019 following a ryecorn cover crop being sown in winter 2018.	https://www.soilwealth.com.au/resources/articles-and-publications/soil-moisture-the- real-winner-in-a-hot-dry-summer-at-the- cowra-demonstration-site-nsw/
Saving time and money with strip-till in WA Podcast, December 2021	Vegetable grower Jake Ryan, from Three Ryans in Western Australia, speaks about their journey to transition their fallow and conventional cultivation to strip-till.	https://www.soilwealth.com.au/resources/podcasts/strip-till-with-jake-ryan/

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Cover crops and strip tillage in organic production - Koo Wee Rup Webinar recording, October 2021	Koo Wee Rup Grower Group - Cover crops and strip tillage in organic production with Dr Kelvin Montagu (20 October 2020)	https://www.soilwealth.com.au/resources/webinar-recordings/cover-crops-and-strip-tillage-in-organic-production-koo-wee-rup-grower-group/
Lyndon Orpwood discusses the benefits of strip-tillage to Simplot Australia Video, May 2019	Simplot Australia's Lyndon Orpwood explains how strip-tillage has improved moisture retention and field productivity at Bathurst, New South Wales.	https://www.soilwealth.com.au/resources/videos-and-apps/lyndon-orpwood-discusses-the-benefits-of-striptillage-to-simplot-australia/
Ed Fagan explains why his initial reservations about strip-till and cover crops were dispelled Video, May 2019	New South Wales vegetable grower Ed Fagan explains how strip-tillage and cover cropping complement each other.	https://www.soilwealth.com.au/resources/videos-and-apps/ed-fagan-explains-why-his-initial-reservations-about-striptill-and-cover-crops-were-dispelled/
Strip-tillage for vegetables and potatoes with Steve Peterson (USA) and Ben Pogiolli (QLD) Video, March 2019	Industry experts explain how strip-till saves fuel and time; increases organic matter in the soil; and reduces erosion and compaction.	https://www.soilwealth.com.au/resources/webinar-recordings/striptillage-for-vegetables-and-potatoes-with-steve-peterson-usa-and-ben-pogiolli/
Strip-till in Tasmania – A reduced till farming system Video, December 2019	This video shares the benefits and challenges of using strip-tillage in vegetable production systems, as well as testimonials from growers.	https://www.soilwealth.com.au/resources/videos-and-apps/striptill-in-tasmania-a-reduced-till-faming-system/
Make 2019 the year you have a serious look at strip-till Articles, December 2018	Looking to reduce establishment costs, improve your soil and save time? This article outlines the benefits and challenges of strip-till.	https://www.soilwealth.com.au/resources/articles-and-publications/make-2019-the-year-you-have-a-serious-look-at-striptill/
Reduced till in vegetable production —WHY? Video, May 2015	In this five-minute video, Ed explains why he is using reduced till and some of the great results he's getting—while saving money.	https://www.soilwealth.com.au/resources/videos/reduced-till-in-vegetable-production-why/
Informing irrigation decisions with remote weather stations at Koo Wee Rup Video, November 2021	While checking on the precision agriculture trial at our Koo Wee Rup demonstration site, team member Carl Larsen recorded a short video to share how a remote weather station and attached soil moisture probe are providing practical insights to inform irrigation scheduling decisions.	https://www.soilwealth.com.au/resources/videos-and-apps/informing-irrigation-decisions-with-remote-weather-stations-at-koo-wee-rup/
Using drones to generate farm insights - Drone basics and operations including weed mapping Webinar recording, July 2021	Watch this recorded webinar to learn all you need to know about the legal requirements for drone operators and how drones can help you manage daily challenges including weed control.	https://www.soilwealth.com.au/resources/webinar-recordings/using-drones-to-generate-farm-insights-drone-basics-and-operations-including-weed-mapping/
Innovations from Growave at Hort Connections 2021 Video, June 2021	The Soil Wealth ICP team put together a short video highlight from the Hort Connections 2021 Trade Show, including new innovations from Growave.	https://www.soilwealth.com.au/resources/videos-and-apps/innovations-from-growave-at-hort-connections-2021/
Ag-tech trial turns up the heat on weeds Case Study, February 2021	Problem weeds such as oxalis and nutgrass could be a thing of the past for vegetable growers following an Australian-first trial of microwave weed control technology at our Koo Wee Rup demonstration site in Victoria. Read this case study to find out more.	https://www.soilwealth.com.au/resources/case-studies/agtech-trial-turns-up-the-heat-on-weeds/

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TITLE	SUMMARY	LINK
Uniformity of nutrient availability continues to improve Videos and apps, November 2020	Now in the third year of trials, the benefit of variable rate lime and fertiliser application is starting to pay big dividends at our Koo Wee Rup demonstration site in Victoria.	https://www.soilwealth.com.au/resources/videos-and-apps/uniformity-of-nutrient-availability-continues-to-improve-in-2020/
Soil health a big winner from precision ag trial Videos & apps, September 2020	There have been noticeable benefits to soil structure from the precision ag trial focusing on variable rate nutrition over the past 2.5 years at our Koo Wee Rup demo site in Victoria. Check out a short video and some photos from our latest visit to the site.	https://www.soilwealth.com.au/resources/videos-and-apps/soil-health-a-big-winner-from-precision-ag-trial/
Variable rate technology: Is it right for your farm? Fact sheet, September 2020	This poster provides a snapshot of variable rate application, the options available, why and how to do it, key questions to keep in mind and more information on the practical tips and tools available.	https://www.soilwealth.com.au/resources/fact-sheets/crop-management/variable-rate-application-is-it-right-for-your-farm/
Adoption of precision systems technology in vegetable production Webinar recording, August 2020	This presentation explains the general approach and results from the implementation of high-resolution multispectral satellite imagery used to predict total carrot root yield.	https://www.soilwealth.com.au/resources/webinar-recordings/adoption-of-precision-systems-technology-in-vegetable-production/
Use of remote sensing technology in vegetable weed control and yield prediction Articles, August 2020	In this article, start-up company Hummingbird Technologies describes how the technologies in the Artificial Intelligence and remote sensing space can help vegetable growers to make the right decisions for weed control and harvest prediction.	https://www.soilwealth.com.au/resources/articles-and-publications/use-of-remote-sensing-technology-in-vegetable-weed-control-and-yield-prediction/
Innovations from John Deere at Hort Connections 2021 Video, June 2021	Kelvin Montagu visits the John Deere booth at Hort Connections 2021 in Brisbane to find out new innovations in precision agriculture.	https://www.soilwealth.com.au/resources/videos-and-apps/innovations-from-john-deere-at-hort-connections-2021/
Remote sensing Global scan and review, July 2019	In this global scan, we address the types of remote sensing available, and its applications to vegetable production systems.	https://www.soilwealth.com.au/resources/global-scan-and-reviews/remote-sensing/
Veg and tech: Science fiction or the future of farming? Global scan and review, June 2019	Soil Wealth ICP scanned the watchlist of 24 emerging technologies detected by Agrifutures in 2018 to determine how tech change will influence vegetable growing businesses. This global scan and review covers global innovations in technology, how they are being applied, and what we should be looking for.	https://www.soilwealth.com.au/resources/global-scan-and-reviews/veg-and-tech-science-fiction-or-the-future-of-farming/
Exploring the application of precision agriculture: Koo Wee Rup demonstration site case study Case study, April 2019	Schreurs & Sons and the Soil Wealth ICP team partnered to explore the application of precision agriculture in celery, leek and baby leaf production systems at Koo Wee Rup in Victoria. This case study captures the results from initiatives to improve nutrition, irrigation and drainage management, and insect pest and beneficial monitoring as a basis for soil and crop health.	https://www.soilwealth.com.au/resources/case-studies/exploring-the-application-of-precision-agriculture-koo-wee-rup- demonstration-site-case-study/
Soil health and water use efficiency Fact sheet, October 2018	This practical fact sheet provides guidance on readily available water and soil texture, as well as healthy soil conditions.	https://www.soilwealth.com.au/resources/fact-sheets/soil-nutrition-and-compost/soil- health-and-water-use-efficiency/

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Appendix 8: Further reading

Below publication include extensive lists of references. These and the original publications have been used, together with knowledge on soils and their management, crop physiology and crop nutrition to compile this guide.

Bertino et al. (2022): Growth, nutrient accumulation, and yield of onion as a function of micronutrient fertilization. Brazilian Journal of Agricultural and Environmental Engineering. v.26, n.2, p.126-134, ISSN 1807-1929

Khalid Mahmud Khokhar (2019):
Mineral nutrient management for onion bulb crops – a review, The Journal of Horticultural Science and Biotechnology, DOI: 10.1080/14620316.2019.1613935

Pire, R., Ramirez, H., Riera, J., & Gómez de, T.N. (2001):
Removal of N, P, K and Ca by an onion crop (Allium cepa L.) in a silty-clay soil, in a semiarid region of Venezuela. Acta Horticulturae, 555, 103–109. doi:10.17660/ActaHortic.2001.555.12

Pacific Northwest Extension Publication, Oregon State University, Washington State University, University of Idaho (2001):
Nutrient Management for Onions in the Pacific Northwest. PNW 546

UGA Cooperative Extension (not dated): Onion Production Guide. Bulletin 1198
https://extension.uga.edu/publications/detail.html?number=B1198&title=Onion%20Production%20Guide

Smallbon T. (2018): The influence of crop nutrition on the quality of onion bulbs destined for export markets. Master of Agricultural Science (Research), University of Tasmania.

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