A practical guide for using green crops in New Zealand

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Note: The contents of this guidebook are not individually referenced. Suggested Reading gives further information of specific details at the time of writing. The exclusion of any other green crop information or study is not intentional and readers are encouraged to investigate other resources.

Introduction

This guidebook aims to help New Zealand (NZ) farmers transition from a reliance on synthetic nitrogen (N) fertilisers to sustainable green-crop N. Doing so will initiate long term improvements to soil and water quality AND help farmers achieve more profit.

Definition: Green Crops manage soil erosion, fertility and quality as well as water, weeds, pests, diseases, biodiversity and wildlife in an agroecosystem - an ecological system managed and shaped by humans.

The guidebook has been written to present information relevant for NZ producers and land owners of any scale so that they can make more informed decisions about using green crops. The uptake of green crops, regenerative agriculture and no-till farming has increased rapidly overseas but, at the time of writing, is still in early stages in NZ. Few studies exist to date, specifically related to NZ conditions, of green crops, nor guides or resources. The guidebook and video resources have been created to make it easier for NZ farmers to use green crops more confidently and effectively. Doing so will improve nutrient creation and retention, soil and water quality as well as profitability.

New Zealand Fresh Water Farm Plans commence in 2025 and they address nutrients, soils, irrigation, biodiversity and waterways. N use is specifically regulated because it has led to the decline in NZ's freshwater quality. Synthetic N also damages soil biology and so reduces nutrient cycling and causes further reliance on fertilisers. Synthetic N fertiliser costs doubled during 2020-2022 because it is manufactured from diminishing natural gas deposits. Green crops are an alternative source of N that are now economically viable.

Consumers want sustainably produced food and green crops offer a great opportunity to help farmers meet this demand. The time is right to try green crops on your farm and see the benefits for yourself.

Different types of green crops can be specifically chosen to:

- add nitrogen (N) into the soil (legumes)
- add carbon (C) in to the soil (cereals/grains & grasses)
- smother weeds, reduce diseases and provide habitat for beneficial insects to protect your main crop from pests

Over the years, different green crops have been described with different names such as:
“Cover Crop” - prevent erosion by covering and protecting the soil surface.
“Green Manure Crop” - fertility building, like adding animal manures, includes legumes for N fixation.
“Catch Crop” - capture excess N that otherwise might leach into groundwater.
“Flowering Green Crop” - plants that provide habitat for beneficial insects.
In this guidebook we refer to “Green Crops” as the one simple name for all of the benefits above.

This guidebook focuses on using green crops for growing vegetables but the contents also apply to:

- Fallow rotations in arable cropping & grazing systems
- Inter-row plantings in viticulture & orchards

- Edible mixed species for stock grazing
- Catch cropping to absorb and minimise N leaching after N-rich crops or grazing rotations

This guidebook is also summarised in 3 video resources.
Available at: ourlandandwater.nz/green-crops
Video 1. Benefits of using green crops
Video 2. Planning for successful green crops
Video 3. Sowing and growing green crops

ABOUT THE AUTHOR

Dr. Dom Ferretti researched Climate Change for 12 years at NZ's National Institute for Water and Atmospheric research (NIWA) and in the USA. In 2009 he returned to his roots and began organic farming, following in the footsteps of his Grandparents, Father and Uncles who were Italian market gardeners. Over the years, he witnessed the negative effects of chemical farming on the health of farmers and the environment. He's followed organic methods to farm in a way that has a good outcome for both the environmental and economic sides of farming. In 2016, he shifted from a high-input farming system, with large scale compost production, to a low-input style of farming, using green crops. This maintained quality produce and resulted in a more balanced and profitable way of farming.

In 2022, Dom and soil consultant, Sjef Lamers, carried out a research project, funded by the Our Land and Water, National Science Challenge, 2022-2023 Rural Professionals Fund. See Appendix D for more information on the research project "Can green crops capture enough nitrogen for vegetable growing in NZ". The short answer was "Yes they can" and further funding was granted from Our Land and Water, through the Impact Extension Fund "Publishing resources to increase uptake of horticultural green crops". This has enabled the production of the guidebook and videos.

"I hope you find the guidebook and videos useful and that you just take the first step in growing a green crop on your farm. Once you do you will see the benefits for yourself and never look back."
Dom Ferretti - Farmer and Consultant in Green Crop Management.

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1. Benefits of green crops.

1.1. Erosion, Soil Quality and Organic Matter

“The nation that destroys its soil, destroys itself.” - Franklin Roosevelt

In New Zealand around 192 million tonnes of soil are lost to erosion each year.

Green crops can protect soil - a farm's most valuable asset - from eroding away. Recovering lost soil from unprotected areas left bare or fallow is impossible, very difficult or expensive - so prevention is by far the best option. We simply cannot afford to lose fertile soil from production areas, yet some of New Zealand's most productive soils experience large amounts of erosion every year. For example - sloping land, such as Pukekohe market gardens, is especially prone to water erosion and areas in the Canterbury plains are especially prone to wind erosion.

The roots of green crops hold soil together. A dense stand of many species (occupying different root profiles) is best to protect against erosion from rainfall, flowing water and wind. But any green crop that covers the soil is better than nothing where unprotected bare “fallow” soil is left exposed to erosion.

Exudates from the living green crop roots feed healthy populations of soil fungi that bind soil particles together into aggregates. These aggregates resist erosion and increase the amount of water and air held within soil which gives better root growth and improved plant health.

Living green crops, as well as their decaying mulch, slow rain drops before hitting the soil surface to further reduce soil compaction and crusting which enables better plant growth.

Green crop roots hold soil together. Cereals, grains and grasses have extensive roots systems and are particularly effective.

Aggregated lumps of soil are visible.

Table 1 Improved soil quality from green crops.

1.2. Nutrients, Leaching

Primary aim	Secondary Benefits
Protect soil from water and wind erosion	• Better adaptation to climate change - increased heavy rainfall and high winds • Less sedimentation in waterways and loss of aquatic habitat • Protects soil biology from direct sunlight and from overheating
Form soil aggregates	• Further reduce soil erosion & runoff • Increase water & air infiltration • Improve soil tilth • Decrease soil bulk density • Less soil structure damage and erosion from cultivation • Promote root growth and improve plant health. • Regenerate tired soil from machinery compaction and/or over - cultivation

, Soil Carbon & Biology.

"We know more about the movement of celestial bodies than about the soil underfoot." Leonardo Da Vinci, 1452-1519.

This remains true in 2023. 1 teaspoon of soil contains about 10 billion living microorganisms and only a tiny fraction have been studied.

In legumes, bacteria live in small growths on the roots called nodules. Within these nodules, N fixation is done by bacteria (e.g. rhizobia). N fixation by legumes is a partnership between a bacterium and a plant. In this process, legume plants can fix N out of the atmosphere and into plant biomass. Total N accumulation from legumes can reach about 300 kg N/ha in just two months of spring growth.

N nodules visible on faba bean roots

After the green crop is killed (terminated) this N is then released into the soil over time as it decomposes. This delayed release means that green crop N can have a lower leaching risk compared to highly-soluble synthetic N. Green crop N can still deliver bulk N for target crop growth. Managed correctly (see section 4.1) green crops can therefore have a lower environmental impact compared to highly-soluble synthetic N.

Carbon (C) is also sequestered into green

crop biomass and depending on management can mitigate greenhouse gas emissions. The large amount of biomass captured by green crops (Dry Matter accumulation in 2 months can be over 10 t/ha) increases soil organic matter (SOM) which is a large reservoir of C, N and other plant nutrients, and is of crucial importance for soil structure and fertility. Green crops improve SOM and soils can then hold more water and nutrients, reduce N & phosphorous (P) leaching as well as reducing irrigation demand.

Cereals, grains and grasses have a higher proportion of roots compared to legumes and a higher C:N ratio (see below). Using cereals/grains in green crops builds SOM that becomes a significant source of on-going plant available N from mineralization to enhance long-term farm performance.

If you want to see exactly how much N is in a green crop it is easy to measure. But average yields will suit most situations and you can look up these values online.

Measuring how much N is in a green crop (from Clark, 2012)
A good way to determine exactly what your green crop has achieved. Field sampling is quick and lab analysis is quite cheap. Required steps are:
1. Estimate the biomass from a sampled area to get green crop yield (kg/ha).
2. Send a sub-sample of the green crop to a lab to measure the proportion of N.
3. Multiply biomass yield by N proportion to get total N (kg N/ha).

For further details on sampling and calculation see Baldwin and Creamer

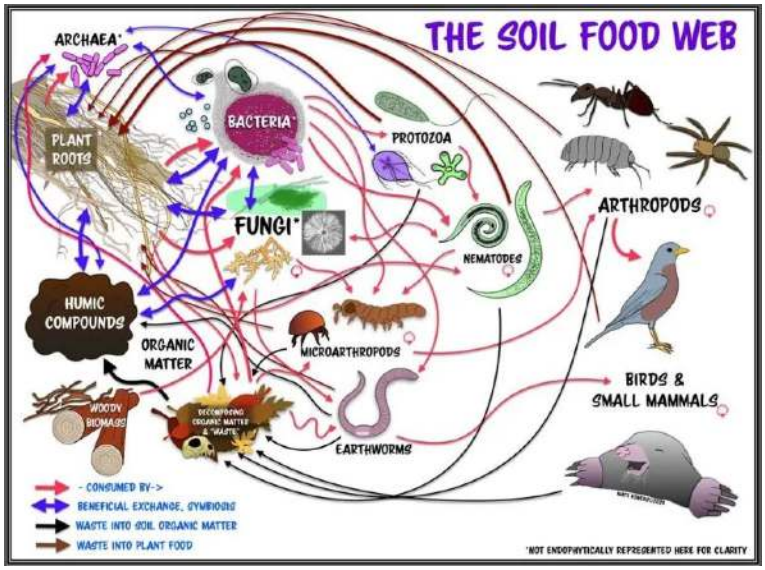
Table 2 Nutrients and Soil Carbon from green crops.

Primary aim	Secondary benefits
Legumes fix N into soil	• Reduce synthetic N fertiliser reliance and production from natural gas • Reduce input costs. • Can reduce N leaching into groundwater.
Green crops (esp. cereals/grains/grasses) catch unused N and prevent leaching	Help to absorb excess field water, further reducing leaching
Accumulate N in green crop biomass	Higher C:N ratios provide nutrition over multiple years
Capture Phosphorous with buckwheat	Reduce P fertiliser costs and phosphate leaching
Increase soil C and SOM	• Greater nutrient and soil water capacity. • Less leaching. • Increased production from less irrigation. • Sequester CO2
Use biomass residue as mulch.	• Conserve water • Suppress weeds • Food for soil biology via the soil food web

One of the most important contributions of green crops to soil health and crop performance is that of soil biology. More efficient nutrient cycling is achieved through larger and more varied populations of bacteria, fungi, micro- and macro-arthropods and earthworms. Living roots in the green crops feed exudates, organic acids, and sugars to fungi in a symbiotic relationship – which in return deliver nutrients and water to the plants from a far greater soil volume, 10-1000 times more! In this way, the entire soil food web is

nourished by living plants and root systems.

Underneath growing green crops and their residues, the soil surface is protected from damaging sun, wind, and rain, creating an environment similar to a soil-building forest floor. Microbes are able to flourish throughout the soil profile and right up to the soil surface. When the mature green crops are returned to the soil, the fertility is available for the next crop(s). Increased SOM from green crops enhances soil microbiology with subsequent increases to nutrient cycling, nutrient and water availability and crop yields.



The Soil Food Web. Source: symsoil.com

Table 3. Improved soil biology from green crops.

Primary aim	Secondary benefits
Use mulch to provide a habitat for soil microbes to flourish up to soil surface - copies soil building environment of forest floors	Better adaptation to climate change, increased heavy rainfall and high winds
More soil microbes, micro and macro arthropods as well as more earth worms	• Better soil structure • More efficient nutrient cycling • Feeds soil biology with diverse root exudates which supports a larger and more diverse population of healthy bacteria and fungi, further improving soil structure as well as access to

Green crops can accumulate high levels of both N and C.

But high N levels can cause:
1. Very high possibility of leaching
2. Microbial blooms in the soil and rapid SOM breakdown (especially after tillage when oxygen levels are high).

A large and diverse population of soil biology is crucial for long term stability of the system. However, to minimise SOM breakdown, it is important not to create a microbial bloom from excessive tillage.

Tillage is the main culprit for SOM breakdown as it creates high oxygen levels in the soil and faster consumption of SOM.

This is one of the reasons for the increased uptake and success of "no-till" and “regenerative” farming.

Explaining C:N ratios
The carbon-to-nitrogen ratio of organic matter is the amount of carbon relative to the amount of nitrogen present expressed as a ratio. The ideal Carbon:Nitrogen (C:N) ratio for green crops is 24:1 – 24 units of C for each unit of N. This is because to stay alive, microbes need a C:N ratio near 24:1 - about 16 parts of C are used for energy and 8 parts for maintenance. Under these optimum conditions, soil microbes can spur release of nutrients like N, phosphorous and zinc to crops.

The C:N ratio can significantly impact:
- **Crop residue decomposition, particularly residue-cover on the soil.**
- **Crop nutrient cycling (predominantly N).**

For low C:N ratios (<20), N is released rapidly into the soil for immediate crop use. When the C:N ratio is between 1 and 15, rapid mineralization and N release occurs, so N is readily available for plant uptake. However, microbes consume the residue faster and so the soil is covered for less time. That lessens the time green crop residues protect against erosion and suppress weeds.

For ideal C:N ratios (~20–30), there is an equilibrium state between mineralization and immobilisation. Residues decompose in a timely manner to release plant nutrients and build SOM, maintaining a balance between soil cover that ultimately breaks down. Mature alfalfa hay has nearly the perfect balance that soil microorganisms prefer with a 25:1 C:N ratio. Microbes consume it quickly and leave little excess C or N.

For high C:N ratios (>30), microbial immobilisation occurs, where the soil microbial populations may take N from the soil in mineral form (e.g. nitrate). This mineral N is said to be immobilised and not readily available for plant uptake.

C:N ratios of some green crop residues.

Vetch/Hairy Vetch:	11		
Mustard:	14		
Phacelia:	10-15		
Tillage radish:	10-19		
Vetch:	15		
Clovers:	15-20		
Ideal Microbial Diet:	24:1		
Mature Alfalfa Hay:	25		
Pea Straw:	29		
Rye (Vegetative):	26		
Rye (Flowering):	37	Barley & Oat Straw:	70

1.3. Weeds, Pests & Diseases.

Green crops can reduce reliance on herbicides by reducing weed growth. Green crops and their residues can eliminate or reduce weeds in cash crops in three basic ways:

- **Smothering weeds** so that they are outcompeted by the green crop and the weeds do not receive enough water and nutrients.
- **Shading weeds** so that they do not receive enough light to grow beneath the growing green crop canopy or beneath the killed green crop residue.
- **The Allelopathic effect** in which chemicals released from some decomposing green crops are toxic to weed seed germination and weed seedling growth.

A vigorous stand of growing green crops can easily suppress weed seed germination and growth because it outcompetes weeds for light, water and nutrients. This is especially beneficial when green crops replace fallow periods in vegetable rotations - weeds are suppressed as well as herbicide usage and soil cultivation are also reduced.

After the green crop is terminated, leaving the thick residues on the surface is an option for suitable crops (see section 4). Doing so can continue to suppress weeds by reducing light, warmth and moisture during the growth of the following cash crop.

Corn growing through mulch from a vetch green crop that was terminated by roller crimper. Source: advancecovercrops.com

Note that as the residue of a green crop mulch decomposes it becomes less effective at suppressing weeds over time. The decomposition rate depends on temperature, rainfall, cultivation as well as the C:N ratio of the residue (lower ratio = faster decomposition, higher ratio = slower decomposition). With planning (see section 2), your cash crop canopy can become large enough while it is growing to keep suppressing weeds even while the green crop residue decomposes.

To suppress some parasitic nematodes, mustard, rape and other brassicas are often incorporated into winter green crop mixes to clean up the soil. These plants have been shown to suppress a wide range of nematodes. Brassica green crops can decrease fungal and mould pathogens present in soil and can be an effective form of biological control.

Take care if you have on-going problems with soil pathogens since the presence of extra residue that remains after a green crop can sometimes act as a host for the pathogen or an organic food source that encourages pathogenic growth. In the case that you have existing, or foreseen, pathogen problems carefully check compatibility of pathogens with different green crops before you plant. Your seed supplier should be able to offer advice or consult online resources.

Flowering green crops are often used to support populations of beneficial insects. The insects are attracted to the shelter, moisture, pollen, honeydew, nectar and insect prey associated with the green crop. The population of beneficial insects increases as the green crop flowering peaks. If well timed, this will match the peak insect pressure of summer crops and the beneficial populations become so large that they move into the vegetable crops to control pests. Using green crops in this way is now common practice to partially or fully control some pests and reduce chemical use – a method know as Integrated Pest Management (IPM).

A flowering green crop can attract beneficial insects to protect you cash crop. Hover fly on flowering mustard shown here.

Table 4. Common green crops used to protect vegetable crops

IPM Green crops	Beneficial insects attracted	Pests Controlled
Buckwheat, Alyssum, Phacelia	Laby Bugs, Lacewings, Hoverflies, Parasidic wasps	Whitefly, Cabbage White Butterfly, Diamond Back Moth, Tomato Potato Psyllid.

Table 5. Weeds, Pests & diseases from green crops.

Primary aim	Secondary benefits
Reduce weeds	Reduce disease carryover in some weeds species.
Partially or fully controlling pests by attracting beneficial insects to flowering green crop species	• Spray residue on crops and soil reduced or eliminated • Spray runoff into waterways reduced or eliminated • Withholding periods constraints removed
Reduce reliance on agrichemicals (herbicides, pesticides, insecticides, etc)	• Save inputs costs as well as labour and fuel costs for application. • Help safeguard personal health as well as that of your family, farm workers, neighbours, community and ecosystem. • Protect healthy soil biology. • Reduce chemical run off into NZ streams and rivers.
Reduce disease pressure, incl nematodes	Improve soil quality, reduce erosion, add nutrients and SOM

2. Planning for successful green crops

There are many different types of green crops, so when planning be aware that there are “horses for courses”. For example, consider what you want the green crop to do at the particular season you plan to grow it.

The first approach is to plan ahead and grow a green crop that best suits the crop you want to grow afterwards.

The second approach is to grow a green crop for your soil type, season and climate or for a specific benefit (i.e. erosion control) and then, after the green crop is finished, you choose a cash crop that works at the time.

2.1 Prioritise your needs

In the first approach of planning ahead, identify the most important cash crop needs.
Cash crop needs:

- Quick or long-lived cash crop
- Gross feeder, high N needed for success
- Planted or direct-seeded
- Root profile, shallow or deep rooted
- Moisture sensitivity, won't tolerate too wet or too dry
- Low N crop, adversely affected by too much N
- Early season crop for higher profit
- Tolerance to weeds
- Tolerance to pests, caterpillars, slugs etc
- Crop quality very important for storage/grade. e.g. pumpkin defects

“Most horticultural crops will have quite specific requirements so it won't be too hard to pick the most important needs. Getting clear on these priorities helps you choose the most effective green crop to create the right conditions in the soil for success”. Video 2.

In the second approach, you want to grow a green crop to improve your farm or soil, and are not thinking about a cash crop. Identify the most important needs of your farm or soil.

Farm/soil needs:

- Control soil erosion
- Improve soil quality
- Improve drainage
- Break up sub-soil pan
- Increase soil organic matter (SOM)
- Alleviate tired soil from compaction and/or over cultivation
- Increase N and fertility
- Increase capacity of soil to hold water and nutrients
- Reduce leaching
- Improve soil biology
- Reduce weed pressure
- Reduce soil parasites/diseases

Green crops can regenerate depleted soil or alleviate problems that come with a new block of land or have developed over many years of cropping. Grow a green crop to avoid a fallow or if soil quality or productivity has fallen below acceptable limits.

These needs can be quite broad but identifying them gives a clear starting point and guidance on the best green crop or blend to choose. Remember that the green crop may overcome problems quickly, or it may take a couple of rotations to be fully successful.

2.2 Pick a green crop to meet your needs

After prioritising what your cash crop (or soil or farm) needs from section 2.1, you then identify the goals for the green crop. Identify the purpose of the green from the list below.

Purpose of green crop:

- Control erosion
- Quick cover
- Produce biomass
- Break up compaction or soil pan
- Build SOM
- Feed microbial population
- Capture N
- Catch N
- Improve P and K cycling
- Suppress weeds
- Create habitat for beneficial insects to protect other crops
- Create pollinator habitat
- Grow as a companion to cash crop
- Graze livestock

While the number of variables to consider might seem overwhelming at first in practice it is usually very easy to work out what green crops to choose and how to manage them.

In planning ahead: you'll know the cash crop you want to grow.

Let's take a couple of examples (carrots or pumpkins). Since these have very different

Tillage radish is effective at breaking up a soil pan (above). Tic beans and lupins capture N. Oats and cereal rye catch N and have extensive roots systems to break up compaction (L to R, below).

needs it will immediately point you to the type of green crop to grow.

For the carrots example, your preceding green crop goal might be to break up compaction and build SOM as those two aspects will allow carrots to grow more easily and access more water and nutrients throughout a deeper soil profile. Additionally, carrots don't need too much N and you need a clean seedbed. So, grow a green crop that doesn't capture too much N (not too many legumes). You will need to incorporate the residue into the soil first to create a clean seedbed to sow the fine carrot seeds into. Possibly you might grow another green crop, beside or within the carrot crop, to provide IPM. Knowing these priorities you can look through the resources (*e.g.* Appendix A) to choose a green crop to grow. Reasonable choices for spring carrots could be tillage radish, cereal rye and oats, for example.

Pumpkins on the other hand require more N so N-fixing legumes should be added into the green crop and ideally, the residue could be left on the surface as a moisture-saving and weed-suppressing mulch for the long-lived crop. So your green crop goals might be: produce biomass, capture N and suppress weeds. Knowing these priorities you can then look through the resources (*e.g.* Appendix A) to choose a green crop to grow. Reasonable choices for spring-planted pumpkins could be peas and oats or vetch and cereal rye, for example.

If you are not planning ahead for specific cash crops but want to overcome specific issues of your farm/soil it should be fairly easy to choose a green crop to alleviate the problem. For example, to reduce compacted soil a good choice is tillage radish and perhaps cereal rye too.

Usually, there are multiple issues to address so opt for a multi-species green crop mix. A green crop monoculture is usually avoided unless you have very specific needs.

When choosing a multi-species mix try not to add too many varieties into the mix (e.g. more than 8) because the most vigorous species dominate and you are paying for some seeds that don’t get a chance to grow.

After growing a green crop for specific issues (e.g. erosion control or IPM), the type of green crop used will point you towards certain cash crops that would benefit most from the remaining residue. For example, if you grew buckwheat to help protect brassicas from summer pests then the buckwheat residue will decompose quickly and release only a small amount of N - so for a cash crop, consider something fast growing and not too reliant on high N (e.g. lettuce). Another example, if you grew a multi-species mix, with cereals/grains as well as legumes, to protect soil from winter erosion then you could utilise the thick residue for growing long-lived summer crops such as melons or outdoor tomatoes. This approach is totally OK and will usually work out within crop rotations. But be aware that if you only grow a narrow range of crops, planning ahead may be best so that you don't find yourself with limited options following a green crop that was grown for a very specific purpose.

To select a green crop that will give you the required benefit for your farm see Table 6 and Appendix A for information about the different green crops available. Talk to your seed supplier for multi-species options, or connect and discuss with other experienced farmers, consultants or online resources.

Table 6. Common Green crops available in NZ and their benefits. For more detailed information see Appendix A.

Green Crop	N fixation	C:N ratio	Good Biomass	Long-lasting mulch	Relieves compaction	IPM
Clovers	Y	Low	Y			
Faba beans	Y	Low	Y			
Lupins	Y	Low	Y			
Peas	Y	Low				
Vetch	Y	Low	Y			
Barley		High	Y	Y	Y	
Black Oats		High	Y	Y	Y	
Cereal Rye, Rye corn		High	Y	Y	Y	
Wheat		High	Y	Y	Y	
Alyssum						Y
Mustard		Low				Y
Tillage radish		Low			Y	Y
Buckwheat						Y
Phacelia			Y		Y	Y

Bear in mind that if you are aiming for a high N green crop there is a higher risk of N leaching. To reduce the risk of N leaching consider growing a green crop blend that includes cereals/grains to delay N release, catch unused N and and increase SOM. See Appendix B for long term N losses over 5 year vegetable rotations where an oats green crop had significantly lower leaching compared to lupins and fallow treatments.

Lighter, free-draining soils also pose a greater risk of leaching compared to heaver soils. By increasing SOM using green crops, or compost, it aids the development of healthier soils with increased nutrient and soil water holding capacity (i.e. less leaching risk). Higher SOM also increases resilience for prolonged dry periods as well as increased biological activity, nutrient cycling and availability.

Consider using soil moisture probes for managing irrigation so that you don't irrigate or fertilise when soils are near field capacity. Also spread nutrient applications, rather than adding all at once.

Use the SVS tool N-sight to help figure out what N you can expect from a green crop as well as guidance on if, when, and how much, of other other supplemental N sources are required to grow your cash crop. See section 2.4 and Appendix B for more.

The practicalities of growing the green crop itself are just important as the actual benefits of the green crop. Consider these extra points to make sure you consider other factors and have everything needed for success.

Other factors for a successful green crop:

- ✓ Consider if a low-spreading or tall-vigorous green crop is best
- ✓ Decide how and when to sow
- ✓ Check if soil temperature is warm enough to sow
- ✓ Check if frost risk important
- ✓ Consider if green crop might need irrigating
- ✓ Consider how to terminate the green crop
- ✓ Consider what and how to sow or plant afterwards
- ✓ Required equipment available
- ✓ Plan for time/labour to do the work
- ✓ Consider a backup plan if the green crop is late to establish or terminate

2.3. Green crops for different seasons.

In practice, green crops on market gardens are generally chosen to be ready for specific crops planted out in spring, summer or autumn. In many parts of NZ soil temperatures are too low to utilise N released from decomposing green crops in winter. Most of the green crops grown in market gardens will need to capture high N and SOM to maintain fertility as the frequent cultivation of market gardening causes losses to soil N and C.

Your location and microclimate will determine which green crops grow well at your site and what are the seasonal options. Consult your seed supplier for advice at first. By growing your first green crop you will gain experience of what works for your farm.

Sometimes there is no specific plan but you have a window of opportunity to plant a green crop. Such an opportunity arises when you have an area that might otherwise be left bare/fallow or if soil quality and/or productivity has fallen below acceptable limits and the area needs regeneration. In this case you might not have a particular cash crop planned to follow the green crop, or your rotation plan must change, but you some cash crop will fit later. If you are just looking to put some green crops in to add general benefits and regenerate tired areas then consider these **Seasonal Recommendations:. Remember - any green crop is better than none! There are no real mistakes as any green crop is good for the soil.**

Spring Mixes, such as peas and oats, can replace a fallow period and jump-start soil biology after winter before planting of a cash crop later in spring or summer. The growing green crop provides extra residue and biological diversity for the soil.

Early Summer Mixes, such as peas, oats, faba beans, buckwheat add biological diversity, suppress spring weeds, produce N, and cycle nutrients. Use ahead of late summer/ autumn plantings of winter veg. Because these mixtures consist of both cool and warm season species, plant after the last frost risk and when soil temperatures reach 12-15°C.

“The spring and early summer mixes are very good at catching N that is released from mineralisation of SOM during the warming spring/summer months. Green crops are a

great way to catch and store this N for using later and prevent the high risk of N leaching during fallow periods" Video 2.

Midsummer Mixes, such as peas, oats, faba beans, radish, buckwheat and sunflowers, are the perfect opportunity to implement very diverse green crops into a cropping system. Converting summer sun into biomass and soil nutrients improves the biological health of your soil. These mixes are the perfect "double crop" to follow a summer harvested crop to build the soil and prepare for a spring crop.

Late Summer Mixes, such as peas, oats, faba beans, radish, buckwheat and cereal rye, provide a terrific window of opportunity for both warm and cool season species to be used together. Warm season species will decline after the first killing frost, leaving the cool season species to continue to thrive and be productive. These green crops grow throughout winter are used ahead of spring planted crops.

Autumn Mixes, such as cereal rye, faba beans, radish and clover, are seeded into or after autumn-harvested crops are beneficial for the soil, but present challenges for establishment during the cooling season. Autumn mixtures vary greatly depending on your goals, planting method, timing, and location. They can be key green crops in market gardens as large areas typically become available after harvesting autumn crops such as pumpkins, squash, main crop potatoes and other root crops. If you are not planting a winter cash crop, consider an autumn green crop as it avoids a winter fallow and significant N leaching. Basic guidelines for autumn mixes are:

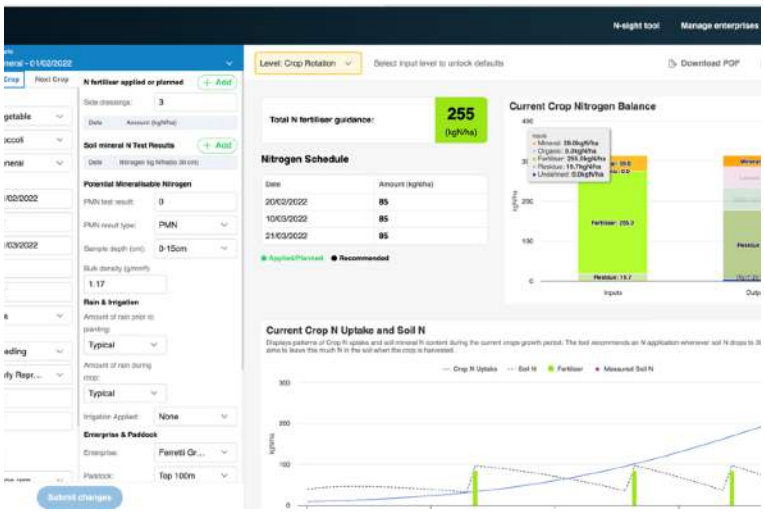
- **Planting 4-5 weeks prior to first frost:** Use any cool season or fast-growing warm season species for significant biomass production prior to frost. This may require broadcast inter-seeding prior to autumn harvest (see section 3.2).
- **Planting 2-3 weeks prior to first frost:** Cool season species that winter-kill at temperatures below freezing or overwintering species are good choices.
- **Planting at, or after, first frost:** With limited heat remaining autumn growth will be limited. So use only frost-hardy cereals/grains/grasses like oats and cereal rye. Use winter-hardy legumes if there is adequate time for spring growth prior to the next planted crop.

2.4 Nutrient needs, using the SVS tool and Economics.

A key aspect of growing horticultural crops is ensuring adequate fertility. Standard practice is to test soil for nutrient levels and then add amendments to obtain desired yield. SOM, total C and Potentially Mineralisable Nitrogen (PMN or HWEON test) are also valuable soil tests for growers wishing to evaluate soil fertility from green crops. Quick-N nitrate soil tests are also an inexpensive on-site test now available.

A new and highly recommended method for working out nutrient needs for vegetable crops is the SVS N-sight tool. This tool, with simple inputs will determine crop requirements and fertiliser guidance. Inputs are soil tests, crops, yield and prior crops (which can be green crops or cash crop residue) and determined values are fertiliser guidance (kg N/ha) and fertiliser application dates. With this information you can input results from Quick-N soil tests generated on-site and then work out if you have enough N available from green crops or if, and when, you need supplemental fertiliser. See the SVS N-Sight example and additional information in Appendix C.

As we have discussed, green crops can offset fertiliser use and therefore reduce input costs. Costs for tillage, pest and disease control are also reduced. They also represent a long-term investment in soil resources. Each farmer can determine how to account for the less apparent, long-term benefits—such as reduced soil erosion, increased SOM, improved soil quality, reduced leaching, as well as enhanced biology and nutrient cycling.



Screenshot of the SVS tool N-Sight. Try the tool at test.svstool.co.nz

Using green crops incurs additional expenses due to seed, sowing and management. Comparing these additional expenses to the benefits of green crops and the returns from horticultural crops, the cost of green crops is comparatively minor.

Legume cover crops add to the short-term profitability because they contribute N to the subsequent cash crop, reducing input costs.

Cereals/grains/grasses, and the C they contain, add to the long-term profitability.

Mix green crops, containing both legumes and cereals, offer the best of both worlds - accumulating N and building SOM with the additional benefit of reducing N leaching.

Take a look at Appendix D to see how green crops increased marketable potato crops in a 2022 Nelson trial. Main findings, and how the cost of green crops compared to compost and synthetic N, were:

- Green crop seeds cost about $400/ha
- After 2 months, the accumulated green crop biomass was about 10 t DM/ha. Equivalent to adding about 17 tonnes of compost/ha, an input cost of about $1100-1700/ha (NZD, 2023)

Due to compounding gains from successive green crops, increasing costs of synthetic N, environmental costs and soil quality improvements, green crop N becomes more economic over multi-year growing rotations.

- The total accumulated N from the legume green crop was (289 kg N/ha).

Both green crops captured ~10 t/ha of dry matter in 2 months.

Input of 150 kg/ha seeds ~$400

+ sow & terminate cost

Equivalent to ~17 t/ha of compost (~20 cubes)

Input of $1100-1700

+ transport & spreading costs

- To match this synthetic N costs would be ~$700/ha (2023 pricing for Urea). To match available N in the first growing season (145 kg N/ha), synthetic N costs would be ~$350/ha
- Green crop management costs are similar or less than compost and synthetic N fertiliser transport and spreading costs.

3. Establishment

3.1. How to sow green crops

The success of sowing green crop seeds depends on getting the seed in the ground at the proper depth. This provides a protective environment and gives access to moisture and nutrients. You may start by sowing your first green crop into a well prepared seedbed with little to no residue. Seed drills and planters will easily give good results. Extremely diverse seed mixes may present some challenges for equipment due to the various seed sizes. Simple green crop mixes may be easier to sow depending on the equipment available.

If there is residue from a previous cash crop, or green crop, no-till drills and planters are preferred because they can cut through residue, create a proper seed trench, place the seed, and cover the seed while leaving the majority of any remaining crop residue in place to protect the soil against erosion. If you do not own a drill or planter, a contractor could sow the green crop seeds for you.

No-till seed drill, planting through green crop residue. Source: farmmanagement.pro

Otherwise broadcasting the seed is an easy option that can work with simple equipment you probably already have. Options are: hand broadcasting, fertiliser spreaders, row crop broadcasters and drones. Broadcasting can sometimes have reduced germination since it can be more difficult for the seed to achieve good seed to soil contact.

To maximise broadcasting success:

- Broadcast seed before rain, or irrigate after. The water drops help the seed contact the soil as well as provide the moisture required for germination.
- Increase the seeding rate by 50-100% over a drilled rate (check with your seed supplier). Some of the exposed seed on the surface may get eaten by birds or get too dry for germination so increasing the seeding rate increases your chances of success.
- If you are able to lightly incorporate the seed into the soil, you will increase the seed-to-soil contact and thus, germination. This can be accomplished by a simple harrow or shallow cultivation with tines or even a shallow rotary hoe/power harrow etc after broadcasting. With some incorporation, the increased seeding rate can be below the 50% level whereas without incorporation, a 100% increase is better.
- Pressing the seed into the ground with a simple roller is more effective than just broadcasting to the surface but a bit less effective than cultivating them in.

“Remember that green crop seeds are a relatively minor cost. If you are committing part of your farm to a green crop and taking time to manage it, do it properly. Don't scrimp on seeds, otherwise you'll end up with a sparse green crop, reduced benefits and, possibly, a lot of weeds too.” Video 3.

Once the green crop seeds have germinated you may need to irrigate. Without sufficient water, growth can be slowed and suppression of weeds from green crops will be reduced along with many other benefits such as N fixation, erosion control, biomass accumulation etc. Growing a good green crop with sufficient biomass ensures the success of your goals and your cash crop.

If you are wanting to capture N, good management can increase legume productivity and N fixation.

- Choose the most appropriate legume for the soil type and environment and varieties that are robust and produce large amounts of biomass.
- Add molybdenum (5 kg/ha)
- Optimise nutrient inputs such as phosphorus
- Use lime to improve the pH of acid soils.
- Effectively manage weeds, disease and insects.
- Use no-tillage or reduced tillage when preparing the area to improve water infiltration and reduce soil moisture loss.
- Sow on time and establish the appropriate plant density.

Note that soil nitrates inhibit legume nodulation and N fixation. At low soil nitrate levels (less than 50kg N/ha in the top meter of soil), legume N fixation is generally high. As soil nitrate levels increase, legume nodulation is reduced and N fixation declines. At nitrate levels of more than 200kg N/ha, nodulation and N fixation will be close to zero. Faba beans are less affected by nitrate levels than peas. Aggressive cultivation, heavy use of synthetic N fertilisers and long pre-crop fallows all increase soil nitrate levels.

3.2. Inter-seeding

Inter-seeding is when green crops are grown between the rows of cash crops. Growing green crops at the same time and place as your cash crops allows maximum productivity from your farm as it allows you to capitalise on the benefits of green crops without taking areas of your farm out of commercial production. Because of this, the practice of inter-seeding is growing in popularity. For a given cash crop the timing and choice of green crop used becomes more critical for success but with good crop choices and management the outcomes can be excellent. A few examples are given below.

A brassica crop with clover inter seeded between the rows.

Cash crops can be sown/planted as usual with standard ground preparation. At the same time as the cash crop is planted, or at a later date, green crop seeds are sown between the rows. The green crop emerges and grows during the lifetime of the cash crop. The purpose of the green crop can be a living mulch to protect from

erosion, fix N for the next cropping rotation, catch surplus N that might be leached or provide IPM to the current cash crop. An example is to sow clover underneath a brassica crop to capture N and protect the soil.

Alternatively, the green-crop can be sown into the cash crop right around harvest so that after harvest a green crop grows to protect and enhance the soil until the next crop rotation. For example, broadcasting high-N legumes into a standing, drying down corn field. Legumes will help the stalky corn residue break down as well as suppress weeds, reducing the need for extra cultivation or weed spraying.

Some crops can be inter-seeded with flowering green crops that attract beneficial insects for pest control. An example of this might be growing alyssum between rows of taller outdoor crops like summer brassicas, tomatoes, peppers, eggplants etc. The alyssum does not interfere with access, sprinklers etc as it only grows about 20-30 cm tall but will attract many beneficial insects to help control insect pests.

Alyssum attracts beneficial insects that protects an outdoor potato crop and summer greenhouse crops (behind bird netting).

In many cases standard crop spacings can remain if the inter-seeded green crop is smaller that the cash crop. When the green crop is taller, then spread rows of green crop rows within the cash crop. For example to help control tomato potato psyllid in potato crops, mixed rows of buckwheat/phacelia (~80cm tall) can be planted every ~10-20m or around the perimeter of smaller plots. The lost production area can be worth it to protect the entire crop from pest damage as well as extra costs from chemicals, fuel and labour.

Companion planting is different to green cropping but can be something to consider if you want to take extra advantage of beneficial insects and further reduce chemical inputs. A specific example is to plant onions adjacent to carrots so that carrot rust fly is deterred by the onion plants and carrots attract insects that prey on onion thrips. While these companion matches are very crop-specific it can be well worth searching online resources for scenarios that suit your farm. The general aim is to reduce mono cropping and grow in harmony with nature rather than fighting against it. Allow nature to assist.

“Essentially, all life depends upon the soil... There can be no life without soil and no soil without life; they have evolved together.” - Dr. Charles E Kellogg, Soil Scientist

4. Managing green crop residue

Despite there being so many benefits of growing green crops, they must come to an end too. Ending them correctly will give you the most benefits and avoid issues such as regrowth, setting seed or clogging machinery. When making a termination plan, consider your goals as well as the needs of the next cash crop. Green crop species, growth stage and weather will impact your decision of when and how to terminate the green crop. Be flexible and choose a method that fits the needs of your cash crops and soil.

4.1 How to end (terminate) green crops

The first decision you face is when to end the green crop.

Early termination occurs when the cover crops are terminated two weeks or more before the next planting, or prior to the green crop plants reaching the reproductive stage. Early termination should occur in drier areas or seasons when moisture use ahead of the next planted crop is a concern. This is because green crops will dry the soil out during their end stages due to water used for growth and transpiration. Soil in which a mature green crop is present can be much drier than fallow soil.

Early Stage

The drawbacks to early termination are that the benefits from your growing green crop, such as adding C into the soil, feeding soil biology, N fixation, and support to beneficial insects, will all end early.

The advantages to early termination include faster decomposition and nutrient cycling, easier planting conditions for the next crop and less late season moisture use.

Late termination occurs when the green crop is killed either at or after planting, or when it is well into the reproductive stage. This is often referred to as “planting green” this method can have significant advantages when well managed.

Advantages of late termination:

- More solar energy will be captured, resulting in more total soil C which will feed the soil biology and increase the water holding capacity of the soil.
- Greater above-ground and below-ground cover crop biomass, which helps to increase water infiltration and reduce surface runoff and soil erosion.

Late Stage

- Legumes will fix more (often double or more) N when growing an extra couple of weeks during spring.
- More nutrients can be scavenged and cycled that might otherwise be lost by leaching or runoff.
- Excess soil moisture will be used and help the soil dry out more and warm up faster during wet springs.
- Planting is easier because green biomass cuts better than dying crop residue that is not yet crisp and dry.

"At the time to terminate a green crop, you may see beneficial insects flourishing and protecting your other crops. After flowering, the biomass becomes much stalkier and the C:N ratio jumps up, meaning it'll take longer to decompose. If you let the green crop set seeds they can become weeds for the next cash crop, or another free green crop to further improve the soil. Remember your goals of when and what you're planting there next." Video 3.

The next decision is how to end the green crop. Some kind of intervention is usually required otherwise the green crop will just keep growing and eventually turn very stalky and go to seed in your field – possibly creating unwanted competition to your later crops.

The termination method that you choose needs to be based on the context of your operation and the goals that you have for both the green crop and the next cash crop.

Tillage Termination
Tillage can terminate green crops and control weeds at the same time. Effective at terminating many types of cover crops, as the roots will be cut and the plant biomass will get incorporated into the soil. Implements like under cutters and high speed discs may cause less disturbance than chisels, plows, rotary hoes, power harrows and tandem discs.

Be aware of the negative effects that tillage and over cultivation has on soil. Every time soil is cultivated soil C and N is lost through oxidation. Additionally, soil structure and biology is lost after tillage making nutrients harder to access and easier to leach.

If you want faster decomposition of green crop residues an optional pass with a slasher mower or flail mower will reduce the material into smaller pieces. This can also make your next sowing or planting operation easier. Faster decomposition could increase the risk of leaching, so weigh up factors as cash crop N uptake, expected weather etc.

Management of tillage will affect the outcome for termination as well as soil health.
- **Standard tillage.** Deep and repetitive cultivation will kill the green crop but will damage soil quality and possibly result in N and C losses.
- **Minimum tillage.** Shallow tillage and only one or two well-timed passes may strike an acceptable balance between killing the green crop but not causing excessive loss of soil quality, N and C.
- **Strip tillage.** Of all the tillage methods, strip tillage would result in the best outcome because only the immediate area surrounding the crop rows are cultivated. This leaves the majority of the area as an uncultivated mulch to preserve soil quality and minimise C and N losses. For success, the green crop choice must be suitable to be terminated by other means (e.g. mowing, frost, chemical). It is possible to modify standard

equipment for strip tillage. For example, rotary hoe tines can be removed from the between-row area so that only the strips where your cash crop is planted are cultivated. Specialist strip-till equipment is available also.

Termination with surface residue intact

The alternative to tillage termination is to leave all of the green crop residue on the surface as mulch. These methods are now considered best practice for many crops due to extensive benefits: less erosion, increased soil quality, C and SOM, nutrient cycling and access, less leaching, weed suppression, and moisture conservation from the mulch created. There are practical issues for success, most importantly the fact that surface mulch means a lower soil temperature which can delay spring crops. Different methods are:

- **Roller Crimp Termination:** Developed over the last 20 years, roller crimpers have become best practice for many crops. This is a far more soil-friendly method than either tillage or herbicide termination because it kills plants without disturbing the soil, ground cover and biology. By crimping, not cutting, the stem and vascular system of a plant, the flow of water, nutrients, and photosynthates is disrupted - effectively killing the green crop plant. A simple concept, but the success of roller crimping termination depends on several factors (see box below). Roller crimping leaves the plants anchored and attached to the soil and the residue in long, un-cut pieces, which leads to maximum uniformity across the field.
- **Freeze Kill Termination:** In cold zones, cold weather can winter-terminate a green crop. The advantage is that no chemical or mechanical inputs are required. Most warm season species will die

Specialised strip tillage implement. Source: sffogia.com

A crimp roller can be a quick and effective way to terminate a green crop

If you don't have a tractor or crimp roller you can do it manually. Crimp termination of green crops works at any scale.

with the first frost, while other cool season green crops (oats, spring peas, and radishes) will be killed at or just below -7°C.

- **Grazing or Mowing Termination:** Plants normally regrow if grazed or mowed while still in a vegetative growth state, but once a plant becomes reproductive, it won't regrow very well. Grazing requires high density stocking rates to get livestock to consume plants in the reproductive stage. Mowing can be effective at later maturity stages; but, because residue is chopped up into small pieces, it can decompose and release N quickly so increases leaching risk.
- **Chemical Termination:** Herbicide use for chemical termination is the common method used by non-organic farmers. Be aware that herbicide use does affect soil biology and can decrease populations of healthy soil biota which in turn reduces nutrient turnover and access.
- **Weedmat and plastic mulch:** Can be temporarily used to prevent regrowth and weeds from rolled, grazed or mown green crops. Can also be used over the crop lifetime for long-lived and heat-loving summer crops such as melons, capsicums, tomatoes and eggplants.

Successful crimping tips.

✓ **Grow suitable species.** Long, succulent or stalky are better than short bendy species.

✓ **Don't use highly diverse mixes.** Highly-diverse mixes will typically have plants at all stages of maturity. Simple mixes like cereal rye and vetch or oats and peas work well as the crop maturity of both species generally match up.

✓ **Increase the seeding rate and sow earlier.** Sowing green crops at a higher rate provides adequate ground coverage (Biomass goal is at least 9 t/ha). Select species that survive until you terminate (especially if after winter frosts) to outcompete and suppress weeds. Sow at twice the recommended rate to get the biomass quantity you need for organic weed management. Cereal rye is very popular - it's winter hardy, matures earlier than other cereals/grains and effective at suppressing weeds.

✓ **Timing is important.** For most species, crimp during the window of susceptibility - at anthesis, or when the plant is flowering and shedding pollen. It can seem like a long wait to reach this stage, but early crimping won't work. Chemical producers can crimp earlier and spray herbicide, at a lighter rate, on the injured green crop.

✓ **Roll twice if required.** Crimping before high winds can prevent the green crop stems lying across the ground in every direction (lodging), which makes it difficult for planters and seed drills. Lodging isn't as much of a concern with succulent legumes like tic beans and vetch because they're much easier to crimp than grains. Adding weight or down pressure can help too.

4.2 How to sow or plant afterwards

After a green crop has improved your soil quality and fertility you can sow or plant your cash crop into the area and reap the rewards.

Planting after tillage termination.
Planting straight away into the freshly cultivated green crop residue can give your cash crop access to the largest overall amount of N available from the decomposing green crop residue. It can be important to get the cash crop established as soon as possible so that it's growth and N uptake is early enough to match the peak period of green crop residue decomposition and N release. The N release rate mainly depends upon moisture and temperature but soil biology levels are also important. Guidelines for temperate climates during the spring/ summer period are approximately 4-6 weeks for max N release.

Minimum tillage of the green crop residue will leave larger pieces that will slow down N release. Suitable crops to handle larger pieces of residue are potatoes, tomatoes, pumpkin, etc. If the green crop residue is first cut into small pieces (e.g. mowed) before tillage a quicker N release will occur. This can make the planting operation easier but will create a higher risk of N leaching.

Planting later after partial or full residue decomposition may be necessary for many direct sown crops e.g. carrots, onions. The sowing/planting operation may be easier after residue decomposition but is best done following lower N green crops to minimise the risk of N leaching.

Strip tillage is a better option as it can give a good result for delicate crops without losing benefits of undisturbed soil and mulch between the rows.

Minimum tillage leaves larger residue pieces that are acceptable for growing some crops, such as potatoes here.

Planting after termination with surface residue intact.
If you are able to manage green crop reside and sow/plant in this way it will give the greatest benefits to soil quality, fertility and crop health. However panting through the thick layer of green crop residue presents challenges both for the practical operation itself as well as the sensitivity of many young vegetables to the presence of residue. Sowing/planting through the surface residue is best suited to crops such as pumpkin,

squash, sweetcorn, outdoor tomatoes, capsicums, eggplants. Soy beans are often grown in this way so this method would be well suited to processing peas and beans.

To sow or plant other crops through the thick residue mat requires more specialist equipment that are able to separate/open the residue mat and perform the operation without getting clogged up with the green crop residue.

- Pneumatic seeders, seed drills or modified seed drills
- Standard planting machines or modified planting machines
- If you don't own this equipment it might be possible to hire a contractor to trial the process before making the investment.

Crimp and plant in one pass. Source: rodaleinstitute.org

Use green crops you will see improvements to the health of your soil AND your crops. This health improves with each successive green crop.

Green crops will allow you to transition from a reliance on synthetic N fertilisers to sustainable green-crop N, giving you more profit and improving soil and water quality.

Start now and the details will become clear along the way. There are plenty of online resources and discussion groups to help you if needed or just reach out to a seed supplier, consultant or other farmers.

Sweetcorn planted through mulch of crimp rolled green crop. Source: fieldcropnews.com

"The future depends on what you do today." - Mahatma Gandhi

This guidebook is also summarised in 3 video resources.
Available at: ourlandandwater.nz/green-crops
Video 1. Benefits of using green crops
Video 2. Planning for successful green crops
Video 3. Sowing and growing green crops

APPENDIX A. Green crop choices

Usually, there are multiple issues to address so multi-species green crop mixes are commonly used. A green crop monoculture is usually avoided unless you have very specific needs.

When choosing a multi-species mix try not to add too many varieties into the mix (e.g. more than 8) because the most vigorous species dominate and you are paying for some seeds that don't get a chance to grow.

Legumes

Legumes can fix N from the atmosphere and accumulate it into the soil. To maximise on this renewable N source ask your seed supplier to inoculate seed with compatible N-fixing rhizobia. Inoculated seed will usually have a white dust on them. Adding molybdenum at 5 kg/ha will also maximise N fixation as this element is required by the rhizobia bacteria. Legumes also prevent erosion, suppress weeds and add organic matter into the soil.

Remember that all green crops provide yield improvements beyond those attributable to N alone. These may be due to mulching effects, soil biological activity, soil structure improvements leading to better moisture retention and crop root development.

Clovers (Legume)
Clovers supply good quantities of N (about 300 kg N/ha/year). They stabilise soil, withstand traffic and are a food source for pollinators. Generally used as an important pasture legume and grown together with perennial grasses for grazing forage they are also very useful in orchards, vineyards and market gardens. Consult with your seed supplier for specific advice as there are numerous clovers (e.g. Arrotas, Crimson, Gland and Persian are annual clovers with good biomass and will nodulate on common strains of bacteria). Some specific features are: very large hollow stems at maturity making them suitable for crimp roller/crimper termination (e.g. Persian); large biomass production (e.g. Crimson); nectar production, pollination and IPM (e.g. Crimson, Persian); fast growth and weed suppression (e.g. Arrotas).

Faba Beans, Tic Beans, Broad Beans (Legume)
Faba beans can grow and thrive in cool wet soils, and are one of the highest N fixing legumes (>300 kg N/ha) also yielding high biomass (>10 ton Dry Matter/ha). The vigorous taproot can reach depths of 50-130 cm. A good choice for autumn and spring green crops. Easy to terminate but residue breaks down and releases N quickly.

Lupins (Legume)
Lupins are cool season annual legumes that accumulate plenty of N (110-170 kg N/ha) and have deep taproots to mine water and nutrients. Peak biomass is just as the flowers (usually blue, purple, yellow or white) are about to bloom. If left to flower, lupins can attract beneficial insects. Lupin stems are hollow so mechanically crush or break easily so are a good choice for minimum tillage or roller crimping. Planting cash crops after lupins is usually trouble-free as the residue breaks down quickly. Lupins are susceptible to many

fungal and viral diseases, including phytophera, so should not be grown in the same field for at least 3 years. Lupins do not tolerate poorly drained soils.

Peas (Legume)
Peas are usually chosen for their N fixing potential (150-300 kg N/ha) and they are also fast growing. Their biomass is succulent and decomposes very quickly so it's not a good choice for a weed-suppressing mulch. Once established, peas can withstand heavy frosts but termination is easy at all growth stages. Peas don't pose any weed threat.

Vetch/Hairy Vetch (Legume)
Vetch produces abundant biomass and is one of the best N producers (>300 kg N/ha), providing enough N for many vegetable crops. It establishes easily, is winter hardy and is very effective at loosening soil. Its' vines can grow to about 3.5 meters long so can present challenges with wrapping around equipment. Vetch biomass is succulent with a low C:N ratio of 8- 15 so it is easy to terminate, breaks down rapidly but will not build up long-term SOM. At mid-bloom can be terminated by mowing or undercutting.

Cereals/Grains

Cereals and grains used for green crops are winter hardy with extensive root systems and good weed suppression potential. They absorb unused N from soil, thrive in low-fertility soils and are quick to provide ground cover.

Cereal Rye/Ryecorn (Cereal/Grain)
Cereal Rye is the most cold tolerant cereal and is well suited to winter green crops. It grows rapidly and forms a dense stand (90-180 cm tall) with an extensive fibrous root system that alleviates compaction. It's also the most drought tolerant cereal, so grows well in sandy and rocky soils. Tolerating a wide variety of soils and climates, rye is one of the most commonly used green crop grains and is a very effective autumn catch crop for N, scavenging 10-45 kg N/ha. Can be sown later than most other green crops since it germinates and grows well in cold weather. Vigorous spring growth suppresses weeds through competition and allelopathic chemicals. Producing a large amount of biomass that is easily terminated it can also be a very effective weed-suppressing mulch as it has a high C:N ratio and persists for a long time before decomposing. Allelopathic chemicals can suppress weeds formally weeks as well as hinder following direct-seeded crops.

Black Oats (Cereal/Grain)
Black oats look similar to common oats, but are larger in size and deeper rooting. Black oats produce a large amount of biomass and increase SOM. They are easy to establish, grow well in cool weather and are easily killed mechanically. Oats provide extra weed suppression from their alleopathic activity and compared to other cereals, oats are more tolerant to wet and heavy soils with moderate fertility, drainage and low pH.

Barley (Cereal/Grain)
Barley grows quickly and can produce more biomass in a shorter time than any other cereal crop. Excellent for erosion control and weed suppression. Tolerates dry conditions and light soil. Barley develops it's deepest, fibrous root system as a winter green crop but as a spring crop, it still holds soil together well. Barley is a good catch crop for N, scavenging about 35 kg N/ha and is a quick biomass source to improve soil structure and water infiltration.

Wheat/Triticale
Extensive fibrous root system that prevents erosion, scavenges nutrients and builds soil structure. High biomass production and well suited for weed suppression. Winter hardy.

Brassicas

Brassicas grow rapidly in autumn to produce good amounts of biomass. The have a good ability to scavenge nutrients and attract beneficial insects if allowed to flower. Most brassicas release chemical compounds that can be toxic to soil borne pathogens and pests. Consult your seed supplier for advice as there are many options (Alyssum, Arugula, Kale, Mustard, Rape, Swede, Tillage Radish, Turnip). Some are suitable for grazing forage (e.g. Kale, Rape, Swede, Turnip) but also offer benefits for regenerating tired compacted soil and catching unused N during growth. Popular brassicas are:

Alyssum
Effective weed suppression and excellent for attracting beneficial insects - predatory wasp species that feed on caterpillars, aphids, and other pest insects. Does not tolerate prolonged dry periods well.

Mustard
Mustards bio-fumigate the soil during decomposition, proving to be toxic to many soil pathogens and pests. Potato quality and yield can increase by growing mustard in potato rotations and root rot in pea rotations can reduce by growing mustard green crops. The standard type is Yellow Mustard, which has fumigating effect. Caliente Mustard, has a much stronger fumigating effect.

Tillage Radish
Rapid growth and great at breaking soil pans with deep taproots. Residue breaks down very quickly and inhibits some annual weeds from germinating. Scavenged nutrients are readily released back into the soil for the subsequent crop. The large root channel left behind is nutrient rich, improves water infiltration and provides access for cash crop roots through compacted soil layers. During decomposition, radish bio-fumigates the soil which can reduce pest and nematode populations.

Other flowering green crops

Buckwheat. Very quick to establish, vigorous growth, low moisture usage and good weed suppression. Flowering can occur within about 4 weeks and continue on for ten weeks, attracting many beneficial and pollinator insects. An excellent choice for IPM. Buckwheat is an effective P scavenger, succulent, easy to terminate and decomposes rapidly. Can set seed easily so be careful if your next crop is very weed sensitive.

Phacelia. A quick growing biomass/SOM builder (can produce 6-16 t/ha of biomass in 14 weeks) and a good N scavenger (37-60 kg N/ha). Also has a great root structure to break up clay soil as fibrous roots can reach 75 cm deep. Main use is as pollinator or IPM pest control as beneficial insects are attracted to blooms that flower when days are longer that 13 hours. Winter kills at -8 Celsius.

APPENDIX B. N losses from 5 year vegetable rotations with green crops

At the time of writing, there is no long-term field study of green crops in NZ. So to test how N leaching is affected by green crops a modelling tool was used to simulate N losses from 5 year vegetable rotations with or without the inclusion of different green crops.

The model used was the Agricultural Production SIMulator (APSIM), developed jointly between Australian and NZ researchers. Within APSIM, the component used was the Simple Crop Resource Uptake Model (SCRUM).

Following the field trial described in Appendix D, which investigated using legume/grain green crops as an alternative source of N, horticultural modelling using APSIM reflected the field trial but over a longer period. The soil was configured with three layers: top 0-20 cm, middle 20-70 cm, and bottom 70-100 cm. Lupins were used as the closest approximation for tic beans in the APSIM/SCRUM simulation. Oats were used to investigate grasses/grains since mixed green crops were not a valid input. The five-year horticultural crop rotation cycle is given in Table 1. Four scenarios were investigated:

- S1: Fallow with Fertiliser – a vegetable crop rotation with fallow periods and fertiliser applications.
- S2: Fallow no Fertiliser – a variation of S1, with all fertiliser applications removed.
- S3: Lupins – fallow periods replaced with Lupins (no applied fertiliser).
- S4: Oats – fallow periods replaced with Oats (no applied fertiliser).

From the APSIM model simulations the key observations of soil mineral N in the top (Figure 1) and middle (Figure 2) soil profile are:

S1, Fallow with fertiliser, has frequent periods of very high soil mineral N in both the top and middle layers, relative to the other three scenarios, coinciding with periods of fertiliser application.

S4, oats, has the lowest soil N, especially during fallow periods. This is because the oat crop uptakes soil N more effectively than lupins and no crops are present

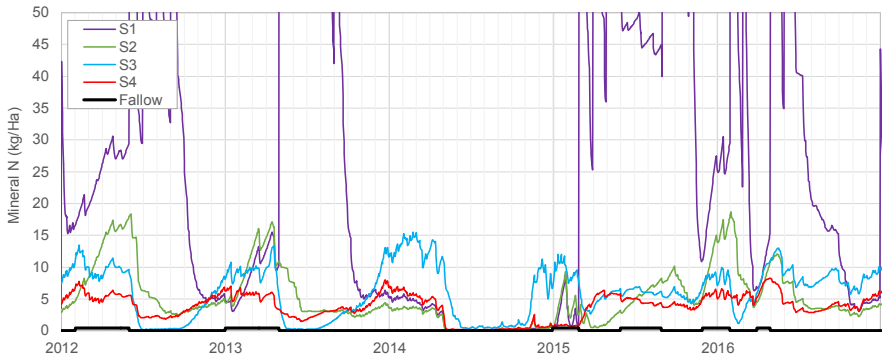


Figure 1. Top soil layer – Mineral N.

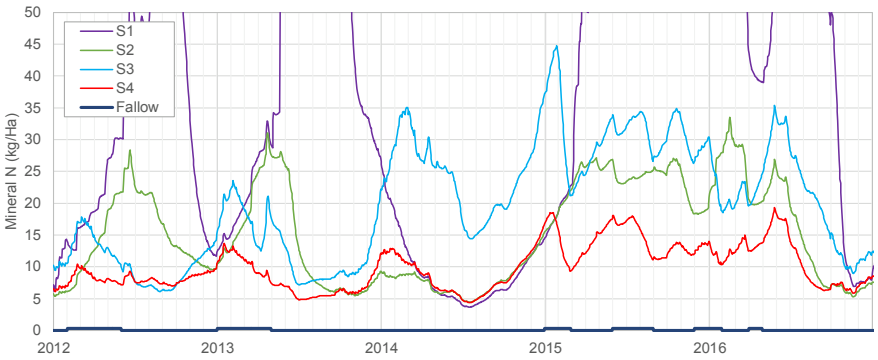


Figure 2. Middle Soil layer – Mineral N.

during S1 and S2 fallows.

S3, lupins, variations of soil mineral N over time are similar to oats (S4) and Fallow no Fertiliser (S2) but with greater variation in magnitude because of legume N fixation. Additional N is fixed when the lupins are present, which results in a change in N dynamics during subsequent periods when other crops are present.

Simulated N leaching from the bottom of the soil profile is presented in Figure 3, and the total N leached over the full five year crop rotation presented in Table 2. Key observations are:

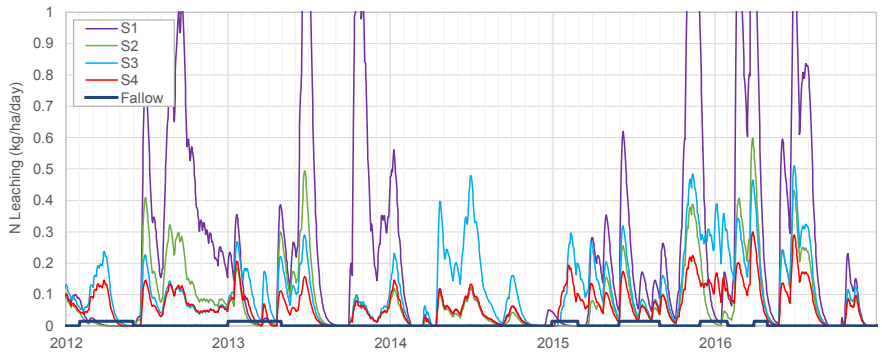


Figure 3. N Leaching from the bottom soil layer.

S1, fallow with fertiliser, has significantly higher N leaching than S2 (fallow without fertiliser), potentially indicating excessive fertiliser application.

S4, oats, showed the lowest level of leaching overall, due to additional N uptake of the oats crop in comparison to the fallow periods of S1 and S2.

Lupins, S3, had a higher level of leaching than oats because lupins add N to the system through N fixation. Lupins had a lower level of leaching compared to fallow with fertiliser (S1).

Table 1. Crop rotation

Year	Month	R2
1	1	Barley
	2	Fallow 1
	3	Fallow 1
	4	Fallow 1
	5	Fallow 1
	6	Onions
	7	Onions
	8	Onions
	9	Onions
	10	Onions
	11	Onions
	12	Onions
2	1	Fallow 2
	2	Fallow 2
	3	Fallow 2
	4	Fallow 2
	5	Potatoes
	6	Potatoes
	7	Potatoes
	8	Potatoes
	9	Potatoes
	10	Potatoes
	11	Potatoes
	12	Oats
3	1	Oats
	2	Oats
	3	Oats
	4	Oats
	5	Carrots
	6	Carrots
	7	Carrots
	8	Carrots
	9	Carrots
	10	Carrots
	11	Carrots
	12	Carrots
4	1	Fallow 3
	2	Fallow 3
	3	Lettuce
	4	Lettuce
	5	Lettuce
	6	Fallow 4
	7	Fallow 4
	8	Fallow 4
	9	Brocolli
	10	Brocolli
	11	Brocolli
	12	Fallow 5
5	1	Fallow 5
	2	Brocolli 2
	3	Brocolli 2
	4	Fallow 6
	5	Barley
	6	Barley
	7	Barley
	8	Barley
	9	Barley
	10	Barley
	11	Barley
	12	Barley

The simulations verified that monoculture legume green crops increase N into the soil but also increase N leaching over five year vegetable crop rotations, verifying earlier studies that legume monocultures increase N leaching.

Table 2. N leached over 5 year rotation

Scenario	N Leached (kg N/ha)
S1, Fallow & fert	959
S2, Fallow no fert	298
S3, Lupins, no fert	439
S4, Oats, no fert	237

Modelling indicates that legume green can be used within horticultural crop rotations to increase soil mineral N and supplement, or replace, synthetic N fertilisers, depending on the crops grown. Modelling indicated lower increases in soil mineral N from cereal/grain green crops but less leaching.

Combing cereals/grains with legumes is best. N accumulation is high and leaching is reduced.

APPENDIX C. Using the SVS tool with green crops

If you are new to using green crops and have a standard practice of using synthetic N fertiliser to produce your crops it is understandable to have uncertainty in using green crops to provide some of your N. Valid questions are:

- How much N will a green crop produce?
- When will you get it back?
- Is there anything you can do to reduce leaching of green crop N?

The SVS N-Sight tool can be used to evaluate the effect of green crops in your rotations before committing to planting them. While not perfectly precise and accurate the indications given help increase your understanding of green crops and how N fertiliser rates might reduce if you grow green crops.

Bear in mind that there are a multitude of other positive factors to soil health etc (see section 1) that are not determined or measured but are always additional to N savings. Look also for reductions in N leaching following green crops. Especially if green crops replace fallow periods in your rotations you are likely to see reduced N leaching.

Once you perform a green crop trial you can easily add in Quick-N soil test results to track the development of your fertility throughout the crop life cycle. This brings the N-sight tool simulation in line with the real world so you can gain confidence in using green crops to accumulate N into your soils. If you can trial a green crop somewhere on your farm you will see benefits in N use and soil quality. Through your own trials you will quickly develop experience to manage green crops for successfully on your farm.

Organic producers as well as arable farmers utilise green crops to maintain and improve soil fertility, including N. In many cases, green crops can provide all the N requirements for production. Organic farmers can supplement with composts and N-rich organic fertilisers such as fish meal etc. Arable farmers reduce synthetic N use by including legume cash crops (such as peas or beans) or green crops in rotations.

However, intensive vegetable production has developed in such a way that reliance on chemical N fertiliser has increased and N production from regenerative green crops has decreased.

Use the SVS tool as a stepping stone to start growing green crops within your rotations, produce renewable N on site, improve soil quality and reduce your reliance and input costs for synthetic N fertiliser.

How to use the SVS N-Sight tool to evaluate green crops and fertiliser requirements to produce viable crops.

- **Go to SVS N-Sight tool webpage https://test.svstool.co.nz/**
- **Select Level: Basic**
- **Add crop details: planting & harvest dates. Yield.**

Run simulation by clicking “Submit changes” button to determine the fertiliser recommendation at the basic level to meet the crop demand.

- **To evaluate the affect of a green crop select Level: Crop Rotation**
- **Add details into the "Prior Crop" Section under the Green Manure section.**
- **Add crop details for the prior green crop: planting and harvest dates, yield.**

Here you will have to use the closest match to your actual green crop.
Choices are: Lupins, Mustard, Oats, Phacelia, Rape, Rye Corn, Turnip.
Lupins can be used as an estimate for most legumes (e.g. Faba Beans, Peas, Tic Beans).
Oats and Rye Corn (Cereal Rye) are quite similar. Rape, Turnip & Mustard are all brassicas.
Phacelia is used mainly for integrated pest management, it's residue is useful biomass and it is a good N scavenger.

- **Set Harvest Stage**

This is the termination of the green crop. Options are: Vegetative, Early Reproductive, Mid Reproductive, Late Reproductive, Late Reproductive and Maturity. This setting has an effect on N content of green crop and therefore fertiliser guideline.

- **Set Paddock Loss to 100%**

For green crops that are returned to the soil in-situ, paddock loss needs to be set to 100%. If you were to harvest the grain portion and then use the remaining biomass for a green crop then adjust this value accordingly.

- **Set Residue Treatment**

For green crops the best option is 'None removed'. Other options are: baled, burnt or grazed. Note: currently, there is actually no difference in SVS calculations for incorporating the green crop residue or leaving it on the surface as mulch. The actual residue treatments will have effects as described in section 4.

- **If available, add any soil test results and submit changes again.**

Now you can look at the difference between the basic simulation without the green crop and the Prior crop simulation (with green crop). By looking at these differences you can get a feel for what to expect from the green crop and how it will influence soil N and your expected fertiliser use. **See the "SVS N-Sight tool example" on the next page.**

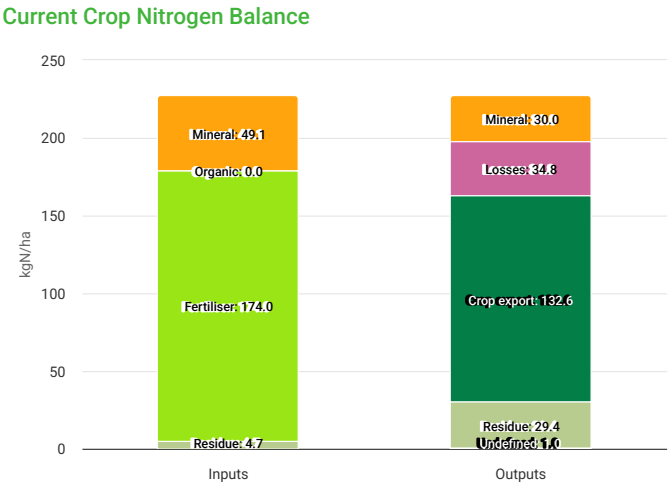
Once you commence the trial you can easily add Quick-N soil test results to track the actual soil N changes that arise after your green crop and keep pushing the simulation back to real changes in your field. Depending on management and seasonal climate etc you may actually accumulate larger amounts of N and save more on fertiliser or it could go the other way if heavy rainfall occurs. In any case you can at least partially reduce N use and any green crop will improve soil quality.

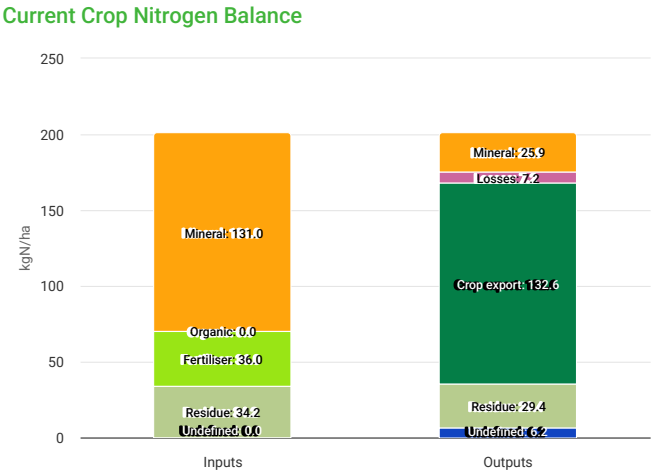
If you are actually using a mix of green crop types (e.g. legumes and cereals/grains to reduce the risk of leaching N) setting a mixed green manure is not currently possible with the N-Sight tool. To estimate the impact of mix green crops, run the simulation with each type of green crop and then make an estimate from the range given by N-sight depending on the ratio of seeds in your green crop mix.

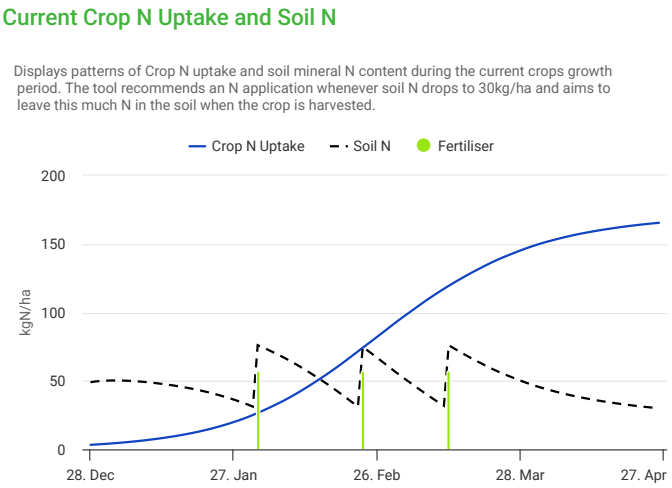
The planting and harvest dates, along with crop yields, are set to those obtained from the green crop and potato trial presented in Appendix D, page 35.

On the left, we have the 'Basic' simulation for the potato crop. Without a prior green crop, the starting Soil N (Mineral) is 49.1 kg N/ha. The corresponding fertiliser requirement is 174 kg N/ha. Losses are 34.8 kg N/ha.

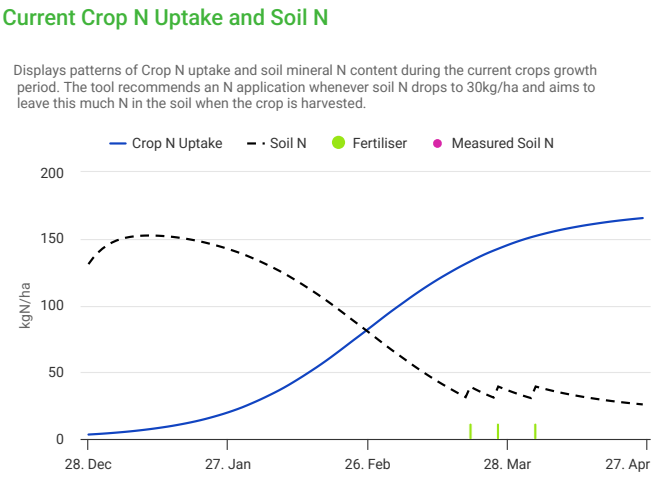
On the right, we have the 'Prior Crop' simulation for the potato crop. With a prior green crop (Lupins with a 10 t/ha yield), the starting Soil N (Mineral) is much higher at 131 kg N/ha. The corresponding fertiliser requirement is only 36 kg N/ha. Losses reduce to 7.2 kg N/ha.







SVS output for Potato Crop at Basic Level



SVS output for Potato Crop with Prior Crop of Lupins

At the time of writing this guidebook the SVS tool is still under development. In particular, the calculation of modelled losses is currently being refined with an improved sub-model. Therefore, the results presented in this example should be considered as indicative of relative differences between treatments only.

APPENDIX D. How green crops increased marketable potato crops in a 2022 Nelson trial

Video Summary of Research Project:
https://ourlandandwater.nz/outputs/green-crops-video/

Research Paper submitted (at the time of writing) to:
NZ Journal of Crop & Horticultural Science

HORTICULTURE

Article: Our Land and Water, New Ground magazine, 2023.

Green manure a viable alternative to artificial nitrogen

Effects of green manure crops on captured nitrogen and potato yields

Why: To quantify how much atmospheric nitrogen (N) spring green crops capture, how much biomass they produce, and the effect on potatoes grown in the lightly crop cultivated residue.

Where: Ferretti Growers, Brightwater, Nelson.

Who: Dominic Ferretti (Ferretti Growers) and Sjef Lamers (Sustainable Nutrition).

What:

- Using synthetic N for vegetable production is subject to increasing costs and regulation, as well as contributing to environmental pollution.
- Synthetic N costs have doubled between 2020 and 2022 in New Zealand and are expected to keep increasing since they are derived from fossil fuels.
- Green crops can capture N in their biomass so offer an alternative N source. Biologically fixed N is renewable and less influenced by increasing production costs.
- Both legume only and mixed green crops were effective at capturing high amounts of N and subsequently improving yields in potato crops.
- Farmers can quickly build the required management experience from on-site green crop trials to maximise economic and environmental benefits.

More:

ourlandandwater.nz/outputs/green-crops-video

Green manure crops provided enough nitrogen to grow a bumper crop of top-quality potatoes, as well as improving the soil structure, in a trial designed to put some data around traditional horticulture practice.

Using green manure to provide the nitrogen (N) his organic vegetable crops need has been a huge success for Nelson market gardener Dominic Ferretti. A scientific trial just finished on his property has showed the practice will work well for any grower, organic or otherwise.

The research project by former scientist Ferretti and consultant Sjef Lamers showed green cover crops are an effective way to reduce N fertiliser bills while maintaining a high yield of quality potatoes.

Harvesting the N-fixing power of legumes is a traditional farming practice, but green manure crops have been replaced on some farms by urea. With the price of fertiliser now increasing sharply, green cover crops might prove more attractive for many farmers.

Ferretti turned to green cover crops to replace the mountains of compost he'd been making to replace N fertilisers.

"We were making compost on a big scale using sawdust and chicken manure, which does make great compost for growing vegetables, but there's a lot of labour and a lot of machinery and costs. I was getting really tired of it. Soil tests were showing we were getting too high in phosphorus, coming from the chicken manure, so we thought this imbalance isn't going to work long term."

His consultant, Lamers, talked him into trying green manure crops instead, sending him mountains of papers and articles from overseas to help convince him.

Caption

"We started using them and they seemed to work pretty well. After not too long, I thought, 'I'm going to give up making this compost and use green crops instead'. It didn't take too long to be quite impressed by the benefits," Ferretti says.

But while green crops were clearly working for him, Ferretti couldn't find any significant published New Zealand-based research about the traditional horticulture practice. He then realised his former occupation as a scientist made him the right person to do it.

"The papers that Sjef was sending me were all for Europe and North America. There was a whole lot of data, but it was hard to relate it to New Zealand. Some of the varieties they grow are different or the same thing with a different name, it's all in pounds per acre instead of kilos per hectare, and it's for growing corn and soya beans in America. It doesn't really make sense to the average Kiwi farmer."

Putting green crops to the test

Ferretti and Lamers designed a simple trial on the Brightwater property where two crops of green crop were grown and a third plot was left bare as a control. The first crop was legume only (tic beans, *Vicia faba*) and the second a legume/grain mix (50:50 tic beans and black oats, *Avena strigosa*).

Each treatment was assigned a plot (48 m x 2.5 m) and replicated five times with a randomised arrangement.

"The legumes fix nitrogen out of the atmosphere. The oats, a grain, don't fix nitrogen but they're really good at mopping it up out of the soil, and they add more carbon but take longer to break down," says Ferretti.

After two months the captured biomass from the legume and mixed green crops were 9.7 ha-1 and 9.9 t ha-1. respectively. This input of about 10 tonnes of dry matter/ha is the equivalent of adding about 17 tonnes of compost/ha.

Captured N was 289 kg/ha for the legume green crop and 198 kg/ha for the mixed green crop. As the research findings note, measurements for the total captured N from the green crops are sufficiently high for the viability of many vegetable crops.

The crops were terminated at the onset of tic bean flowering. The start of flowering is the point when biomass is maximised before excessive conversion to carbon material. To speed decomposition, the biomass was reduced into smaller pieces by two passes with a slasher mower, then incorporated into the top 4 cm of soil with a rotary hoe cultivator.

A week later Agria potatoes were planted – a total of 185 kg of seed potatoes in 15 plots – and harvested 112 days later.

Table 1: Green crop dry matter (DM) biomass and captured N content (%N) for above ground (AG), below ground (BG) and totals. Differences between Legume and Mix are indicated by * for significance at the p<0.05 level and ** for significance at p<0.01. NS indicates differences are not significant.

		DM (%)	DM (kg ha^{-1})	%N	N (kg N ha^{-1})	Total DM, AG+BG (kg ha^{-1})	Total N, AG+BG (kg N ha^{-1})
Legume	AG	11.2**	8345, NS	3.2**	264**	9673, NS	289*
	BG	13.3**	1327*	1.9**	25**		
Mix	AG	13.1**	7230, NS	2.3**	163**	9904, NS	198*
	BG	20.4**	2674*	1.4**	35**		

Potato yields were 33.5, 30.6 and 30 tonnes/ha from the legume, mixed and control treatments, respectively.

Potatoes were graded for quality. The legume treatment had the highest weight and number of marketable potatoes, as well as the largest mean tuber weight compared to the mixed and control treatments.

Throughout the nine-month trial soil tests were conducted, including the levels of the different forms of mineral N, as well as Olsen P, K, Ca, Mg, Na, total carbon and other elements.

The biomass of both the green crops and the potatoes was measured (see Table 1). "We had to cut the plants at ground level, weigh that material and then pull out the roots. We sent it all to Hill Laboratories where they carefully washed the roots, and analysed them and the tops for nitrogen content," says Ferretti.

"The overall results are enough to raise eyebrows," he says. "It was what we expected – the trial went well and we were very pleased."

Benefits for all farm systems

Ferretti says that it's not just organic vegetable growers who could benefit from the research. Any producer wanting to reduce their nitrogen fertiliser use should also take notice.

Synthetic N costs have doubled between 2020 and 2022 in New Zealand and are expected to keep increasing since they are derived from fossil fuels. Regulations for N use are increasing globally and in freshwater farm plans will be required here by 2025 with associated implementation costs.

"We just wanted to get people talking and maybe get them to think, 'I might just try that down in the back paddock', or something. That's all we want people to do at this stage, because as soon as you try it you'll see the results and they'll speak for themselves – and it's a no-brainer from there."

it's not just organic vegetable growers who could benefit from the research. Any producer wanting to reduce their nitrogen fertiliser use should also take notice.

As well as effectively replacing artificial N, the research findings showed that the green crops observably improved soil structure. They can provide extensive benefits to soil and ecosystem health that can assist vegetable production, as well as vineyards and orchards.

Ferretti and Lamers have secured additional funding to study winter-grown green manure crops. Ferretti is now working on a best practice guide for other growers, building on the knowledge gained in the trial.

"We actually found that we didn't need to do that much incorporating into the soil, mixing it in with a rotary hoe. It's actually best left on the surface as residues, a mulch, so that's even less fuel cost.

"I think Kiwi farmers are feeling the pressure. We've got heaps of regulations coming and I believe if we can just get the information to them to try this, even if just using a bit less synthetic nitrogen to begin with, that would be a huge success."

Tony Benny for the Our Land and Water National Science Challenge

APPENDIX E. NZ Seed suppliers and Suggested Reading

A selection of NZ green crop seed suppliers.
KiwiSeed. https://www.kiwiseed.co.nz/ Ph: 03 578 0468
Norwest Seed. https://www.norwestseed.co.nz/ Ph: 03 3077 393
NZ Cover Crops. https://covercrops.co.nz/ Ph: 03 302 7909
Symbiosis. https://symbiosis.co.nz/ Email: seed@symbiosis.co.nz

Suggested reading

A More Accurate Picture of Where Soil Erosion Is Likely, Our Land and Water, New Zealand. https://ourlandandwater.nz/news/a-more-accurate-picture-of-where-surface-erosion-is-likely/

Baldwin, K.R., Creamer, N.G., 2009. Cover Crops for Organic Farms, Organic Production, North Carolina Extension Service. https://carolinafarmstewards.org/wp-content/uploads/2012/12/4-CEFS-Cover-Crops-on-Organic-Farms.pdf

Clark, A., 2012. Managing cover crops profitably, 3rd ed. Sustainable Agriculture Research and Education program handbook series. ISBN 978-1- 888626-12-4. https://www.sare.org/wp-content/uploads/Managing-Cover-Crops-Profitably.pdf

Dirt to Soil: One Family's Journey into Regenerative Agriculture Paperback, September 2018, by Gabe Brown
https://www.chelseagreen.com/2023/5-principles-of-soil-health/

Lowenfels, J., Lewis, W., 2010. Teaming with microbes: The organic gardeners guide to the soil food web. Timber Press. ISBN 1604690224, 9781604690224

Sullivan, D.M., Andrews, N., Brewer, L.J., 2020. Estimating Plant-Available Nitrogen Release From Cover Crops, Pacific Northwest Extension Publishing, PNW 636. https://catalog.extension.oregonstate.edu/sites/catalog/files/project/pdf/pnw636.pdf