Optimising the use of legumes for nitrogen supply to vegetable crops

Stephanie Tabone, 2024 Scholar
New South Wales

July 2025
Nuffield Australia project number 2421

Supported by

Optimising the use of legumes for nitrogen supply to vegetable crops

Scholar contact details

Name: Stephanie Tabone

Organisation: Applied Horticultural Research

Address: Eveleigh NSW 2015

Phone: +61 434 514 846

Email: stephanie.tabone@hotmail.com

Website

Social media: LinkedIn

NUFFIELD AUSTRALIA Contact Details

Nuffield Australia
Telephone: 0456 916 506

Email: enquiries@nuffield.com.au

Address: PO Box 450, Bendigo, VIC 3550

Executive Summary

Nitrogen is a critical input in vegetable production, however rising fertiliser prices and environmental scrutiny are driving interest in biological alternatives. Legumes, through their unique ability to fix atmospheric nitrogen offer a natural solution, yet their integration into modern, high-intensity vegetable systems remains complex.

This report explores how to optimise the use of legumes as a nitrogen source in vegetable cropping systems. It combines current science with global on-farm practice to help growers and advisors better understand how legumes work, and how to manage them to reduce fertiliser inputs, improve soil health, and build system resilience.

The report outlines the biological processes underpinning nitrogen fixation, including the role of rhizobia, soil conditions, residue breakdown, and nitrogen release. It discusses key management strategies such as species selection, inoculation, termination timing, and synchronising nitrogen supply with crop demand. Tools for measuring nitrogen contribution and budgeting are provided to support decision-making.

A key focus is on real-world application. Several case studies are included, covering:

- Cover cropping approaches
- Companion cropping systems integrating legumes with cash crops
- Legume cash crops managed to deliver both income and nitrogen benefits

Each example highlights practical ways growers are trialling, adapting, and refining legume use within diverse farm systems. Lessons from these growers, including successes, trade-offs, and innovation are distilled into actionable insights.

While legumes are not a universal solution, they are a powerful tool. When grown and managed well, they can fix between 50–200 kilograms of nitrogen per hectare, reduce fertiliser use by 20–40%, and deliver a range of system benefits including improved soil structure, biological activity, and reduced emissions.

The report explores how successful use of legumes requires both scientific understanding and adaptive management. There is no single recipe, but by applying core principles, observing outcomes, and refining over time, growers can harness legumes to improve profitability, sustainability, and some independence from synthetic inputs.

Keywords: legume, rhizobia, nitrogen supply, vegetable production

Table of Contents

Optimising the use of legumes for nitrogen supply to vegetable crops

---

Foreword

I grew up in Sydney with little connection to agriculture, however I had a strong passion for science and the natural world. After graduating high school, I studied a Bachelor of Science in Agriculture with First Class Honours at the University of Sydney.

For the past eight years, I've worked in horticulture, with a particular focus on the vegetable sector. My current role is in extension, which allows me to work directly with vegetable growers, supporting them to adopt farming practices that are productive, profitable, and sustainable. I work on the Soil Wealth and Integrated Crop Protection project, funded through the vegetable levy, which bridges research and on-farm application.

Through this work, I've had the privilege of engaging with a wide range of vegetable growers across the country. Many are trialling or adopting cover crops as part of their rotations, to improve their soil health and as a response to the rising cost of inputs, which continue to place pressure on grower margins. One common opportunity I've heard growers talk about is the use of legumes to reduce nitrogen fertiliser costs and environmental footprint. However, the key challenge growers have been facing is how to manage nitrogen release from legumes to match the needs of their vegetable crops.

Figure 1: Author Stephanie Tabone, standing in a mixed species cover crop. (Source: Author)

This challenge sparked my interest in understanding the practicalities of using legumes to supply nitrogen. While the science is well-documented, the on-ground management is complex and often context-specific. I saw an opportunity to explore both the science and the practice, to understand the agronomic detail and system-level thinking required to make legumes work effectively for vegetable production.

This scholarship also came at the right time for me personally. I was ready to grow, not just technically, but professionally and personally. I wanted to challenge myself, meet new people, and shift my perspective.

Working in extension gives me a unique view of the industry working between research and practice. My job is to translate technical knowledge into something relevant and practical. This report is an extension of that work. It aims to equip growers and agronomists with tools, insights and strategies they can apply to their own farming systems, to improve nitrogen use, reduce costs, and ultimately increase the profitability, productivity, and sustainability of the Australian vegetable industry.

Table 1: Travel itinerary

Travel date	Location	Visits/contacts
07/11/2023	Australia	Nitrogen Conference
17/03/2024 – 21/03/2024	Brazil	Post CSC tour
19/08/2024 – 24/08/2024	England	Ben Taylor Davies Ed Lea James Alexander Nicky Cannon Paul Richards Polly Hilton Toby Baxter
25/08/2024 – 05/09/2024	France	Francois Mulet Joelle Fustec Marie Morineau, on David Guy’s farm Stephanie Chanfreau
9/09/2024 – 11/09/2024	Netherlands	Erwin Westers Geert-Jan van der Burgt Jan Willem Bakker Janjo de Haan Ken Giller Lennart Fuchs Lotte van Dueren den Hollander Rogier Scherpbier Weike Vervuurt
12/09/2024 – 13/09/2024	Germany	Meinke Ostermann
16/09/2024 – 20/09/2024	Canada	Anita Speers Bean Haven Blake Vince Brady Cameron Ogilvy Elaine Roddy Iraj Yaghoubian Jack Streef Jeff Cook Jim Clarke Laura van Eerd Lauren Benoit Laurent (Woody) Van Arkle Matt McIntosh
23/09/2024 – 26/09/2024	USA	Beto Perez De Leon Bill Wintermantel Danny Royer Don Cameron Erik Peterson John Warmerdam Kimberly Gibson Richard Matoian

Various 2023-2025	Australia	Andrew Johanson Lachlan Rienke Mark Fritz Val Micallef

Acknowledgments

I'd like to thank Hort Innovation for funding my Nuffield scholarship and making this opportunity possible. I'm also incredibly grateful to Applied Horticultural Research, to both the management and the wider team, for their support throughout this journey.

Thank you to the many growers and researchers around the world who hosted me on farm and were incredibly generous with their time and learnings shared.

A heartfelt thank you to my husband, Marty, for keeping the household afloat while I was travelling, for joining me on parts of my travels, and for the emotional support throughout this journey.

I'm deeply appreciative of my mentors, Dr Kelvin Montagu for his technical guidance and Paulette Baumgartl for helping me digest my learnings and apply them throughout different aspects of my work and life.

Finally, a special thanks to Nicky and Wade Mann, both incredible people and Nuffield alumni, who believed in me and encouraged me to apply for the scholarship.

Abbreviations

%Ndfa	Percent of nitrogen derived from the atmosphere
C	Carbon
C:N	Carbon to nitrogen ratio
GHG	Greenhouse gas
Ha	Hectare
HWEON	Hot Water Extractable Organic Nitrogen
Kg	Kilograms
L	Left
MERCI	Method to Estimate N Release from Cover crop Introduction
N	Nitrogen
N_2	Nitrogen gas
N_2O	Nitrous Oxide
NDICEA	Nitrogen Dynamics In Crop rotations in Ecological Agriculture
NH_3	Ammonia
NH_4^+	Ammonium
NO	Nitric Oxide
NO_3^-	Nitrate
NSW	New South Wales
OM	Organic Matter
Qld	Queensland
R	Right
T	Tonnes
UK	United Kingdom

Objectives

- Explore both the science and on-farm practice of using legumes to supply nitrogen in vegetable cropping systems.
- Provide a practical toolkit of strategies for managing legumes across different geographies, soil types, and growing conditions.
- Improve grower and agronomist understanding of how legumes work.
- Support growers with effective use of legumes as a nitrogen source to supplement fertiliser and reduce costs in diverse farming systems.

*Keep an eye out for "**rules of thumb**" highlighted with this symbol:*

Introduction

Background

The Australian vegetable industry has a production value of $5.7 billion. Only 5% of fresh produce is exported, while 58% is sold fresh within Australia, and 37% is supplied for processing (Fresh Logic, 2024). With most produce staying onshore, high levels of domestic supply can result in downward price pressure, especially where seasonal peaks result in market oversupply.

For vegetable producers, the financial pressure is considerable. On average, production costs account for 23% of total farm income, with fertiliser costs alone representing 8% (Planfarm, 2024). A recent industry survey revealed that 34% of vegetable growers considered leaving the industry in the next 12 months, with over half indicating the rising input costs as the primary reason (AUSVEG, 2024).

At the same time, expectations for environmental sustainability are growing. Producers are feeling the impacts of more regular extreme weather events, while consumers and shareholders are demanding greater accountability.

Although emissions reporting remains voluntary for most producers, new regulations are emerging. Under mandatory climate-related financial disclosures, large companies will soon be required to report their emissions. It is unclear how this will flow through the supply chain, but producers may soon be asked to quantify and reduce their own emissions, particularly scope three emissions linked to fertiliser use.

Nitrogen is at the centre of this conversation. It's a critical nutrient for plant growth, playing key roles in protein formation, enzymatic reactions and photosynthesis (Uchida and Silva, 2000). Yet synthetic nitrogen fertilisers come with high economic and environmental costs. In Australian vegetable systems, synthetic nitrogen use accounts for 17% of on-farm emissions, primarily through soil nitrous oxide (N_2O) losses (Figure 2) (Maraseni et al., 2010).

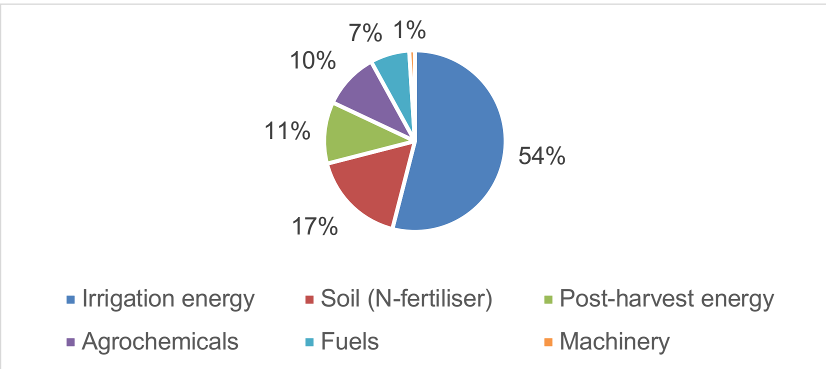


Figure 2: Greenhouse gas (GHG) emissions from farm activities in the Australian Vegetable industry (Maraseni et al., 2010).

When considering the entire nitrogen cycle, nitrogen fertilisers contribute 59% of emissions on-farm, with another 39% from manufacturing and 2% from transport (Menegat et al., 2022). Worse still, recovery of fertiliser applied nitrogen rarely exceeds 50%, with significant losses through volatilisation, leaching, erosion and denitrification (Gonzales-Lopez and Gonzales-Martinez, 2021).

As growers face increasing financial and environmental pressure, many are seeking alternative approaches to nitrogen management. Legumes offer a biological solution, valued for their ability to fix nitrogen, however, their successful integration into modern vegetable systems is complex.

This report explores both the science and the practicalities of using legumes to supply nitrogen, with the aim of supporting growers to reduce input costs, manage emissions, and build more resilient, efficient farming systems.

Legumes as a solution: opportunities and challenges

Legumes have long served as a natural source of nitrogen in farming systems, well before synthetic fertilisers were available. Their success was not based on precision or measurement, but on observation, context, and system design. The challenge today is to recapture that biological benefit within modern, high-intensity vegetable systems, by combining both old principles and new tools.

"*Nitrogen is in the atmosphere, 78% around us. Why wouldn't we make use of it?"* Jan Willem Bakker, Netherlands

The benefits of legumes are well established: nitrogen fixation, improved soil fertility, pest and disease breaks, and enhanced microbial activity (Kebede, 2021). With input costs rising and sustainability under the spotlight, more producers are now considering how legumes might fit into their rotations.

Using legumes as a nitrogen source is not without its challenges. The main challenge is timing – for a vegetable crop to access the fixed nitrogen from the legume, the legume must first die and decompose. This decomposition is driven by microbes, through a process called mineralisation, which converts organic nitrogen into plant-available forms like ammonium (NH_4^+) and nitrate (NO_3^-) (Johnson et al., 2005).

Mineralisation is influenced by environmental conditions like temperature, moisture, soil pH and biology, making the timing of release difficult to predict across seasons, soil type, and legume species (Oliveira et al., 2020).

Vegetable crops also have different nitrogen needs at different growth stages, adding another layer of complexity. If nitrogen is released too early, it can be lost, leading to both environmental harm and wasted nutrients. If released too late, crop yield or quality may suffer.

These are the same risks faced with synthetic fertilisers. While growers have more control over when fertiliser nitrogen is applied, the timing of release of nitrogen from legumes is harder to predict and control. Regardless of the source, once nitrogen enters the soil, biological processes like nitrification and denitrification influence its fate.

Getting it right depends on understanding the system and making thoughtful management decisions. This report explores those decisions in detail, from species choice and timing to on-farm tools and real-world examples. When managed well, legumes can reduce fertiliser use, lower costs, and improve the environmental performance of vegetable farming systems.

Other benefits of legumes in rotation

Beyond their role in supplying nitrogen, legumes offer a range of additional benefits that can improve the overall performance of vegetable cropping systems. Research has shown that legumes can enhance subsequent crop yields and support the development of beneficial soil biology, including plant growth-promoting bacteria and microbes (Guinet et al., 2020; Stagnari et al., 2017; Peoples et al., 2009). They can build soil organic matter – a process that requires both carbon and nitrogen, both of which legumes supply. They can also improve soil structure and moisture retention, mobilise fixed forms of phosphorus and provide valuable pest and disease breaks (Stagnari et al., 2017; Lupwayi and Soon, 2015; Peoples et al., 2009). These broader system benefits make legumes a powerful tool for building healthier, more resilient farming systems.

How legumes fix and supply nitrogen: the science

Nitrogen fixation explained

Legumes have a unique ability to form a symbiotic relationship with nitrogen-fixing bacteria called rhizobia. These bacteria live in the plant's roots and form small nodules, where they convert nitrogen from the air into a form the plant can use. In return, the plant provides the bacteria with a place to live and a supply of sugars as an energy source – a considerable investment to support nitrogen fixation (Newton, 2007; Stacey, 2007).

For this process to work, the right strain of rhizobia needs to be present and compatible with the legume species. The legume sends out chemical signals, and the rhizobia respond and attach to the root hairs, which then curl around the bacteria. This triggers a series of changes in the plant that leads to the formation of a nodule on the root, the specialised structure where nitrogen fixation takes place. This process can commence within a few days after plant germination (Stacey, 2007).

Inside the nodule, the rhizobia convert nitrogen gas (N_2) from the air into ammonia (NH_3) using an enzyme called nitrogenase. The plant then converts this NH_3 into other nitrogen-rich compounds it can use to grow (Farquharson et al., 2022; Stacey, 2007).

The nitrogen fixed is then supplied to actively growing roots and leaves. As the plant matures; flowers, fruits and seeds source nitrogen from what is still available in the soil and from the plant's leaves, stems and roots (Tegeder and Masclaux-Daubresse, 2018). Nitrogen uptake and nitrogen fixation declines during plant maturation and seed filling (Masclaux-Daubresse et al., 2010).

The environment inside the nodule needs to be carefully controlled. Rhizobia require a small amount of oxygen for respiration, but too much oxygen can deactivate the nitrogenase enzyme. To manage this, the plant produces leghaemoglobin, which binds to oxygen and maintains the low-oxygen environment needed for fixation to occur. The presence of leghaemoglobin gives actively fixing nodules a pinkish-red colour, a useful sign that nitrogen fixation is occurring (Figure 3) (Farquharson et al., 2022; Stacey, 2007).

Figure 3: Cowpea nodule, red in colour, indicating successful nitrogen fixation (Dr Naomi Diplock, 2025).

Key points:

- Legumes form a partnership with rhizobia bacteria, which live in root nodules and convert nitrogen from the air into a form the host plant can use.
- The right rhizobia strain must be present and compatible with the legume species for nodules to form and fixation to occur.
- Nitrogen fixed by the legume is not stored in the nodules – it is distributed throughout the roots, shoots, and grain.
- Active nodules appear pink due to leghaemoglobin, which helps maintain the low-oxygen conditions needed for nitrogen fixation.
- For a vegetable crop to access fixed nitrogen, the legume must first die and decompose – it is through this process of mineralisation that organic nitrogen is converted into plant-available forms.

How to maximise nitrogen fixation

Now that we understand how nitrogen fixation works, the next step is ensuring it actually happens and happens well. Nitrogen fixation is not guaranteed. It relies on good crop management and the right conditions. This section explores the key factors that influence effective legume nitrogen fixation, and what growers can do to give the process the best chance of success.

Rhizobia

While rhizobia can naturally occur in soils, the correct strain for the legume and the right quantity, may not always be present to trigger effective nodulation (Peoples et al., 2009). Inoculating the seed with rhizobia at planting is a simple but powerful practice to improve the odds. Rhizobia are one of the most well-researched and reliable biological inputs available, and using the correct inoculant is essential for successful nitrogen fixation (Farquharson et al., 2022). Inoculating with a double rate is recommended for greater efficacy.

Many farmers have found success using peat-based or freeze-dried rhizobia inoculants, which are easy to mix onto seed using an old bathtub, a large shuttle, or even a concrete mixer. These low-cost tools can have a big impact, helping to ensure nodules form early and the crop is set up to fix nitrogen effectively. See Table 2 for examples of inoculant products available.

Table 2: Summary of rhizobia inoculant formulations and sowing considerations, adapted from Farquharson et al. (2022).

Inoculant formulation	Composition	Storage	Application options	Sowing conditions	Sowing window (sow within...)
Peat	High organic matter (OM) soil, milled and irradiated, with rhizobia added in a nutrient suspension	4 to 10°C	✓ On seed ✓ In furrow (liquid suspension)	✓ Moist soil ✕ Dry soil (max 7 days before rain)	Slurry: 24 hrs In furrow: within 6 hrs of mixing
Freeze dried	Concentrated pure cells of rhizobia, water removed under vacuum	4 to 10°C	✓ On seed ✓ In furrow (liquid suspension)	✓ Moist soil ✕ Dry soil	Slurry: 5 hrs In furrow: immediately after dilution
Granular	Clay or peat granules impregnated with rhizobia	Cool, dry	✓ In furrow only	✓ Moist soil ✓ Dry soil	Best sown with seed
Liquid	Suspension of rhizobia in a protective nutrient solution	4°C	✓ In furrow (liquid suspension) only	✓ Moist soil ✓ Dry soil	Immediately after dilution
Pre-inoculated seed	Seed coated with peat inoculant, polymers, and agrochemicals	Cool, dry	✕ On seed ✕ In furrow	✓ Moist soil ✓ Dry soil	2 weeks – 6 months (species variable)

Soil nitrate

High levels of soil nitrate can inhibit nitrogen fixation in legumes. When nitrate is readily available in the soil, legumes delay nodule formation or reduce nitrogen fixation, as it's far less 'costly' for the plant to take up available nitrate than to invest energy feeding rhizobia (Farquharson et al., 2022; Peoples et al., 2009).

- *Nitrogen fixation slows when soil nitrate levels exceed 50 kg N/ha.*
- *At levels above 200 kg N/ha, little to no fixation occurs.*
- *These thresholds can vary depending on the legume species and cultivar.*

pH

Soil acidity is a major barrier to effective nitrogen fixation. Low pH can affect the survival of rhizobia in the soil, reduce nodule formation, and impact the legume plant itself (Farquharson et al., 2022). Interestingly, some rhizobia strains are even more sensitive to pH than the legume host. However, knowing the preferred pH range for the legume species can generally indicate the needs of its microbial partner.

Implementing a liming program and regularly inoculating with rhizobia can help improve nitrogen fixation. Lime also offers additional benefits, such as reducing toxic levels of aluminium and manganese, while improving the availability of key nutrients like phosphorus, calcium, magnesium, and molybdenum (Peoples et al., 2012). For guidance on pH preferences by species, refer to Table 3.

Table 3: Recommended pH ranges for common legumes, measured in calcium chloride (Farquharson et al., 2022).

Legume species	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0	8.5	9.0
Narrow leaf lupin & serradella	✓	✓	✓	✓	✓	✓					
Biserrula		✓	✓	✓	✓	✓	✓	✓			
Sub clover (depends on sub-species)			✓	✓	✓	✓	✓	✓	✓		
Soybean			✓	✓	✓	✓	✓				
Peanut				✓	✓	✓	✓				
Pea, faba bean, vetch				✓	✓	✓	✓	✓	✓	✓	
Lentil					✓	✓	✓	✓	✓		
Burr medic				✓	✓	✓	✓	✓	✓	✓	
Lucerne				✓	✓	✓	✓	✓	✓	✓	
Chickpea					✓	✓	✓	✓	✓	✓	
Strand and disc medic						✓	✓	✓	✓	✓	✓

Nutrition provided to legume crop

Like any crop, legumes need the right nutrients to perform, but when it comes to nitrogen fixation, nutrition matters even more. Without key elements in the soil, nodules may not form properly, rhizobia may struggle to survive, and nitrogenase (the enzyme that fixes nitrogen) will not function at its best.

Phosphorus and calcium are particularly important for both rhizobia and nodule development. However, molybdenum is essential for the nitrogenase enzyme itself, making it one of the most critical nutrients for fixation. Deficiencies in cobalt, boron, and copper can also affect nodule function, while potassium, sulphur, and iron support general plant growth and health. A soil test before sowing is recommended to identify any gaps and ensure the legume crop is well supported to fix nitrogen effectively (Peoples et al., 2012; Newton, 2007).

Water

Although different legume species vary in their tolerance to water stress, nitrogen fixation is universally sensitive to dry conditions. Water stress can disrupt several key processes, reducing the energy that is needed for nitrogenase activity, limiting nitrogen metabolism, impairing oxygen regulation within nodules, and restricting nitrogen transport from the roots to the rest of the plant (Plett et al., 2020).

Simply put, without enough water, nodulation and nitrogen fixation suffer. Maintaining good soil moisture helps the legume grow longer, build more biomass, and ultimately fix more nitrogen (Peoples et al., 2012).

Key points:

- Inoculate the seed with the correct strain of rhizobia to ensure successful nodule formation. Refer to the Cover crops for Australian vegetable growers poster for more information on inoculant strains.
- High soil nitrate levels can suppress nitrogen fixation. Avoid sowing legumes into soils with more than 50–200 kg N/ha.
- Healthy legume crops fix more nitrogen. Ensure legumes have balanced nutrition, especially molybdenum.
- Nitrogen fixation is highly sensitive to water stress. Ensure adequate soil moisture, particularly during early growth and nodulation.
- Different legume species have different pH preferences, however soil pH matters. Acidic soils inhibit rhizobia and nodulation. Add lime to correct pH or match species choice to the soil conditions for the best results.

How much nitrogen can a legume add?

Legumes do not just store nitrogen in their nodules. Fixed nitrogen is distributed throughout the plant, including the roots, shoots, and grain. On average, legumes fix (Peoples et al., 2009):

- *15-25 kg of nitrogen in the shoots, for every one tonne of dry matter produced*
- *Total ~30 kg nitrogen per tonne of shoot dry matter, which includes contributions from both shoot, root and nodules*

The amount of nitrogen in a legume crop depends on how much biomass is produced and the nitrogen concentration of that biomass. Therefore, well-grown legumes that produce more biomass will fix and accumulate more nitrogen (Farquharson et al., 2022). The amount of nitrogen in a legume crop (on a dry matter basis) can be estimated using the formula:

Legume N = (%N / 100) × biomass

However, not all nitrogen in the plant is derived from the atmosphere. Legumes still take up nitrogen from the soil. The proportion that comes from fixation is called nitrogen derived from the atmosphere (%Ndfa), and this varies by legume species, environment, and management.

A key point often overlooked is that nitrogen is also stored below ground in the legume's roots and nodules. Studies have shown that 40–55% of a legume's total nitrogen can be present in the roots and nodules (Peoples et al., 2012). This nitrogen pool can be a valuable resource for companion crops or for the next crop in the rotation.

To account for this, researchers have developed root factors, which are multipliers applied to shoot nitrogen data to estimate total plant nitrogen (shoots + roots). For example, if a legume has a root factor of 1.5, then for every one kilogram of nitrogen measured in the shoot, the total plant nitrogen would be estimated at 1.5kg. This provides a more accurate estimate of the crop's full nitrogen contribution to the system (Peoples et al., 2012). Different legumes have different root factors, depending on species and root structure. See Table 4 for a comparison of different legumes, showing their average %Ndfa, nitrogen fixed in shoots, and root factor where available.

Table 4: Comparison of different legumes, showing their average %Ndfa, nitrogen fixed in shoots, and root factor where available (Farquharson et al., 2022; Swan et al., 2022; Peoples et al., 2012, 2017; Peoples et al., 2009).

Legume	% Ndfa (Crop N from fixation)	Shoot-N fixed (kg/ha)	Root factor**
Arrowleaf clover	57	100	
Balansa clover	68	106	
Berseem clover	75	60	
Biserrula	26	32	
Bladder clover	68	29	
Chickpea	54	40	2.06
Common bean	31	15	
Cowpea	73	20	
Desmanthus	32	6	
Faba bean	77	95	1.5

Field peas	62	*56	1.5
Gland clover	62	76	
Groundnut	52	103	
Lablab	58	92	
Lentil	74	71	
Lucerne	60	83	2
Lupins	74	*76	1.5
Medics (Annual)	74	56	
Melilotus spp.	64	115	
Pea	70	108	
Persian clover	67	133	
Pigeonpea	78	59	
Purple clover	65	134	
Rose clover	61	62	1.72
Serradella	31	38	
Siratro	50	44	
Soybean	62	137	
Stylosanthes spp.	82	26	
Subterranean clover	81	65	1.72
Sulla	82	91	
Vetch	80	103	1.5
White clover	68	42	2.22

*calculated using total N from (Farquharson et al., 2022), and root factor (Swan et al., 2022).
** The root factors for all species was unable to be obtained.

How to measure nitrogen in legumes on farm

Below are the key steps to estimating how much nitrogen is being added by a legume crop. To calculate this, the dry matter biomass (t/ha) and the nitrogen concentration (N%) of the plant material is needed.

1. **Collect biomass samples** just prior to termination. Use a quadrat of a known size (e.g. 0.5m x 0.5m, see Figures 4 and 5 below) and place it randomly across the paddock. Cut the plant material at the soil surface and place it in a paper bag. Repeat in multiple locations for improved accuracy.
2. **Dry the biomass** in an oven at 60°C or use a dehydrator until it reaches a constant weight (typically 24–72 hours). Weigh each sample, and subtract the weight of the bag to calculate dry matter. Then use the formula:
   Biomass (t/ha) = (dry weight of sample (g) / area of quadrat (m^2)) / 100
3. **Send a sub-sample to a lab** to test for C% and N%. This will allow nitrogen content to be calculated and the C:N ratio to be determined, an important measure to understand residue quality and how quickly it will mineralise.
4. **Calculate** the nitrogen content using the biomass (t/ha) and nitrogen concentration (N%), using the formula:
   Legume N (kg/ha) = (%N/100) x dry matter (t/ha) x 1000
5. **Estimate roots** by multiplying the shoot nitrogen by the root factor, see Table 4, where available.

Figures 4 & 5: Faba bean crop with quadrat used to estimate biomass (Author, 2024).

Key points:

- Different legumes fix different amounts of nitrogen.
- Nitrogen is stored in both above and below ground tissues.
- On average, legumes can add 30 kg of nitrogen (into above and below ground tissues) per tonne of dry matter.

How does nitrogen become available from legumes?

Once nitrogen has been fixed by the legume, the next step is getting it into a form that the vegetable crop can actually use. This requires the legume to first die, then decompose through the process of **mineralisation**, where organic nitrogen from plant residues is broken down by microbes and released into plant-available mineral forms like NH_4^+ and NO_3^- (Johnson et al., 2005).

Other less significant pathways like **rhizodeposition** or **mycorrhizal exchange**, contribute small amounts of nitrogen, but mineralisation does most of the work.

"The nitrogen cycle is a nitrogen dance - a rhythm of nitrogen circulating throughout the system in a sequence."
Geert-Jan van der Burgt, Netherlands

The nitrogen cycle explains how nitrogen moves through the farm – from the air, into the soil, through plants, and sometimes out again through loss pathways (Figure 6). Understanding where legume nitrogen fits into this cycle enables more effective management, reduced losses, and nitrogen release to be aligned with crop needs.

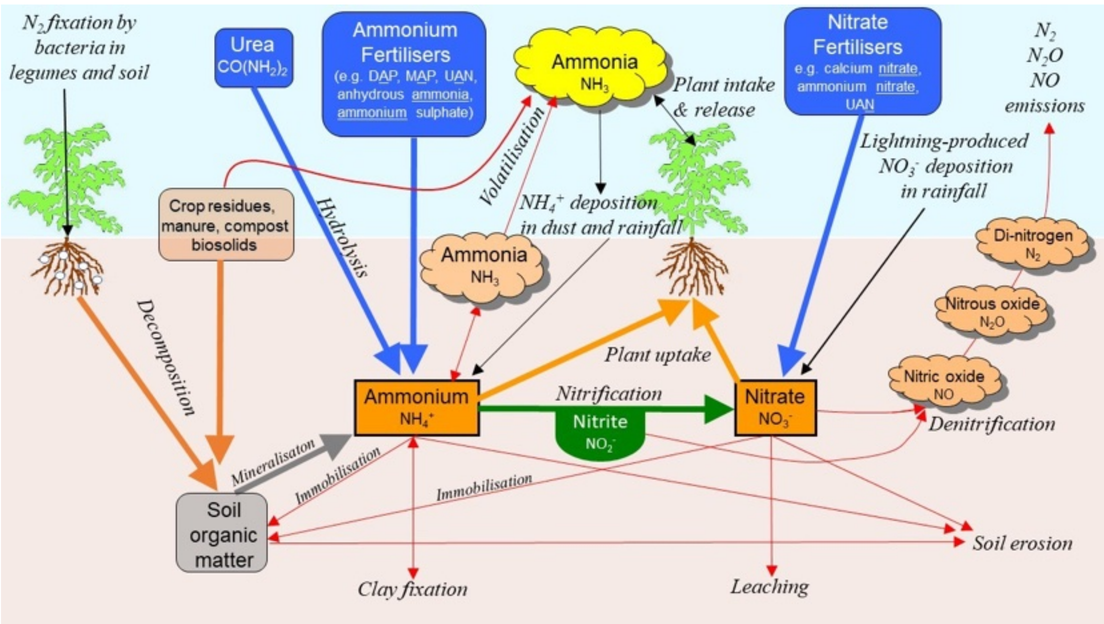


Figure 6: The nitrogen cycle (Schwenke, 2022).

At the heart of it, crops take up nitrogen as NH_4^+ and NO_3^- (Uchida and Silva, 2000). Most plants prefer NO_3^-, as long as the soil pH is in the right range (Plett et al., 2020).

Mineralisation

After a legume is terminated, its residues begin to break down, leading to a push or pull of nitrogen occurring through:

- **Mineralisation**: microbes convert organic nitrogen into mineral forms (NH_4^+, then NO_3^- via nitrification), making it available to crops (occurs under warm, moist, aerated soil conditions).
- **Immobilisation**: microbes 'tie up' nitrogen into an organic form while decomposing high-carbon residues (Johnson et al., 2005).

The Carbon:Nitrogen ratio (C:N) of residue is the key driver.

Decomposition and nutrient cycling are driven by microbes. Microbes need a diet with a C:N ratio of 24:1, with 16 parts of carbon for energy, and eight parts of carbon for maintenance (USDA, 2011). Residues with higher C:N ratios tend to decompose more slowly and favour fungal activity; lower C:N residues decompose faster and release nitrogen.

Table 5: How C:N ratio affects nitrogen availability

C:N	Outcome	What happens
< 24:1	Mineralisation	Microbes consume what nitrogen they need to break down the carbon, and 'release' excess nitrogen in the soil. Decomposition is rapid.
> 24:1	Immobilisation	Microbes scavenge nitrogen to break down the excess carbon. Decomposition is slow, and nitrogen is 'locked up' by microbes temporarily.

The C:N ratios of different cover crops can be found in the Cover Crop Termination Guide for Australian Vegetable Growers poster.

Nitrogen loss pathways

Once nitrogen is mineralised, it is vulnerable to losses if not taken up by a crop. Key pathways are summarised below.

Table 6: Nitrogen loss pathways in the nitrogen cycle (Johnson et al., 2005).

Loss pathway	What it is	When it happens
Leaching	NO_3^- is highly mobile in the soil, and is lost with water or soil erosion	High NO_3^- levels and heavy rainfall or irrigation
Denitrification	$NO_3^- \rightarrow NO, N_2O, N_2$	Waterlogged, compacted or poorly drained soils
Volatilisation	$NH_4^+ \rightarrow$ ammonia gas (NH_3), escapes to the atmosphere	High pH soils, hot and windy conditions encouraging evaporation

N_2O is a potent GHG with a global warming potential almost 300 times that of carbon dioxide (Maraseni et al., 2010).

Why does this matter?

Understanding mineralisation, immobilisation and nitrogen loss is the key to using legume nitrogen effectively. Just like fertiliser, nitrogen from legumes needs to be released when the vegetable crop needs it. If it's released too early, it can be lost. If it's released too late, it may compromise yield or quality.

By knowing what drives the breakdown of legume residues, growers can better match nitrogen supply with nitrogen demand, reduce losses and get more value from the nitrogen they've grown. It is about timing, biology and working with the nitrogen cycle, not against it.

The next section explores factors that affect mineralisation, and with them, the things that growers can start to influence on farm.

Factors affecting mineralisation

Temperature

Temperature plays a key role in how quickly microbes break down residues and release nitrogen. As soil warms, microbial activity increases, accelerating mineralisation (Grzyb et al., 2020).

Table 7: Microbial activity and mineralisation rates at different soil temperatures (Grzyb et al., 2020; Pietikainen et al., 2005).

Soil Temperature (°C)	*Microbial activity and mineralisation rate*
< 10	*Very low*
10 – 25	*Moderate*
25 – 30	*Rapid*
> 30	*Low – microbial activity inhibited by high temperatures*

Soil moisture

Moisture is another crucial driver of microbial activity. Dry soils limit microbial movement, while waterlogging restricts oxygen and slows decomposition (Grzyb et al., 2020).

- *Ideal conditions are moist (but not saturated), well-drained soils, for two to four weeks after termination*
- *Avoid repeated drought-rewet cycles, which disrupt microbial function and nitrogen release*

C:N ratio of residues

The C:N ratio of legume residues is a reliable predictor of nitrogen availability (Fox et al., 1990). The C:N ratio shifts with plant maturity. During reproduction, nitrogen is reallocated to seeds and away from leaves and stems, leading to an increase in C:N ratio of residues. This influences how easily residues break down at different maturity levels, and how much nitrogen is left in the system after harvest (Tegeder and Masclaux-Daubresse, 2018).

- *C:N < 24:1 leads to net mineralisation (nitrogen released)*
- *C:N > 24:1 leads to net immobilisation (nitrogen tied up)(USDA, 2011).*

Legumes generally have more nitrogen and a lower C:N ratio than cereals, meaning they tend to release nitrogen more readily (Swan et al., 2022; Virk et al., 2022).

Lignin and polyphenols

It is not just the C:N ratio, residue chemistry matters too. Lignin and polyphenols make residues tougher and more resistant to decay. While polyphenols and lignins provide functional benefits to plants, such as defence from pest and disease, and structural stability, they degrade into compounds that bind nitrogen and slow its release (Fox et al., 1990). The higher the (lignin + polyphenol):N ratio, the slower the mineralisation (Reeves et al., 2018; Fox et al., 1990; Palm and Saschez, 1990).

Residue incorporation into soil

Incorporating residues into the soil boosts contact with microbes and speeds up decomposition. Even shallow tillage (like discing or strip tillage) accelerates nitrogen release compared to leaving residues on the surface (Sondag et al., 2025; Grzyb et al., 2020; Liebman et al., 2018).

- *Lightly incorporate residues for quicker nitrogen release*
- *In no-till systems, expect slower breakdown unless residues are low in C:N and soils are warm and moist*

Soil properties

Mineralisation is fastest in:

- *Neutral pH soils (6.5-7.5)*(Grzyb et al., 2020)
- *Sandy to loam textures* (Grzyb et al., 2020)

Soil biology

Microbial diversity is the engine room of decomposition. Bacteria dominate during early breakdown, while fungi break down tougher residues later (Grzyb et al., 2020). Moisture, temperature, C:N ratio and residue composition all influence microbial activity. While biological inoculants are available, they are not a primary driver for boosting mineralisation – most soils already host a wide range of native biology capable of breaking down legume residues (Sondag et al., 2025).

What does this mean for nitrogen availability to crops?

Three key questions are often asked:

- How much nitrogen becomes available?
- When does it become available?
- How much does the following crop actually take up?

The answer, as always, is: it depends, but there are some useful averages:

- *30% of total legume residue nitrogen becomes available within 100 days post-termination (Li et al., 2020; Crews and Peoples, 2005)*
- *Peak mineralisation of legume shoots occurs two to six weeks after incorporation under favourable conditions (Li et al., 2020; Crews and Peoples, 2005)*
- *Roots of legumes decompose more slowly than shoots (Li et al., 2020)*
- *Only 10–30% of total legume nitrogen is taken up by the following crop in year one (unless it is supplied as high quality green manure) (Peoples et al., 2009; Crews and Peoples, 2005)*
- *Legume nitrogen incorporated into organic matter mineralises slowly over time (<5–10% per year), providing a long-term reservoir of soil fertility (Peoples et al., 2009)*

Other pathways

While mineralisation is the main way legumes supply nitrogen, other smaller pathways also contribute. These include rhizodeposition, root senescence, and mycorrhizal associations.

Rhizodeposition happens during active plant growth, when legume roots and nodules release nitrogen and carbon-rich compounds into the soil (Virk et al., 2022). This process varies depending on the plant's growth stage and nutrient status and may support nitrogen transfer to companion crops (Kebede, 2021).

Root and nodule senescence also releases nitrogen into the soil. As roots age and die, they begin to decompose, even while the plant is still alive, returning nutrients into the soil.

Mycorrhizal fungi help to scavenge nutrients like phosphorus and potentially nitrogen from the soil, transferring them via a shared hyphal network (White et al., 2013; Baluska and Vivanco, 2012). Some nitrogen exchange between plants may occur this way.

The extent of each of these mechanisms depends on legume species, soil biology and moisture. Their contribution of nitrogen is typically small (<10 kg N/ha) and can be variable (Peoples et al., 2018).

Key points:

- For the vegetable crop to access fixed nitrogen, the legume must first die, then decompose through mineralisation.
- Mineralisation involves microbes converting organic nitrogen into ammonium and nitrate, the main pathway for legume nitrogen becoming plant-available.
- The C:N ratio of residues, along with soil temperature, moisture, and biology, are key drivers of how quickly and how much nitrogen is released.
- Other minor pathways like rhizodeposition, root senescence, and mycorrhizal exchange can contribute small amounts of nitrogen (<10 kg N/ha) but their contribution is variable.
- On average, 30% of legume nitrogen becomes available within 100 days of termination, with only 10–30% taken up by the next crop in year one unless supplied as high quality green manure.

Nitrogen removal with harvested products

While legumes can add significant amounts of nitrogen to farming systems, it's important to remember that much of this nitrogen can be removed from the system when the crop is harvested. Whether legumes are grazed, cut for hay, or harvested for grain, nitrogen is exported in the product.

Grain legumes typically remove the largest proportion of accumulated nitrogen, as most of the plant's nitrogen ends up in the seed. In contrast, grazing or hay production results in smaller nitrogen losses. Legumes left ungrazed or unharvested, like cover crops terminated before seed set, return the most nitrogen to the soil (Guinet et al., 2020).

Table 8 highlights how nitrogen inputs from legumes can vary widely depending on the legume species, management, and what is removed. For example, field peas often remove over 100 kg N/ha in grain, resulting in a neutral or even negative nitrogen balance. In contrast, pastures like lucerne or subterranean clover often show a positive net nitrogen contribution, especially when less nitrogen is removed (Peoples et al., 2012).

This underscores the importance of considering how much nitrogen is exported when legumes are used as cash or forage crops, and planning rotations to recapture or supplement nitrogen in the following crop.

In addition, harvesting legumes for hay or grain requires additional farm traffic, increasing the risk of soil compaction, particularly in wet conditions. This can undermine the very soil health benefits that legumes are intended to support and should be factored into rotation planning.

Table 8: Nitrogen fixed, removed and net input from various legumes across sites in Australia (Peoples et al., 2012).

Location	Legume	Total N_2 fixed (kg/ha)	N removed and lost (kg/ha)	Net input of fixed N (kg/ha)
Moora, WA	Subterranean clover	136	11 in wool + 29 lost	+96
	Lupin	162	106 in grain	+56
Naracoorte, SA	Subterranean clover	132	8 in wool + 24 lost	+100
	Field pea	125	128 in grain	–3
	Faba bean	180	120 in grain	+60
Horsham, Vic.	Lucerne–medic	154	7 in wool + 22 lost	+125
	Field pea	262	151 in grain	+111
Hopetoun, Vic.[1]	Vetch (sand)	130	89 in hay	+41
	Field pea (sand)	125	136 in grain	–11
	Vetch (clay)	77	71 in hay	+6
	Field pea (clay)	48	56 in grain	–8
Rutherglen, Vic.	Subterranean clover	220	10 in wool + 42 lost	+168
	Narrow-leaf lupin	200	99 in grain	+101
Wagga Wagga, NSW	Pasture–legume mix[2]	71	8 in wool + 17 lost	+46
	Vetch	83	8 in wool + 23 lost	+52
	Field pea	65	104 in grain	–39
	Narrow-leaf lupin	75	105 in grain	–28
Junee, NSW	Lucerne	256	11 in wool + 46 lost	+199
	Field pea	235	148 in grain	+87

[1] Identical experiment on two soil types.

[2] Forage mix: 41% balansa clover, 29% subterranean clover, 17% berseem clover, 13% arrowleaf clover.

Key points:

- Harvesting grain legumes removes the most nitrogen from the system, reducing the residual benefit for following crops.
- Grazing and hay also remove nitrogen, though typically less than grain harvest.
- Ungrazed or unharvested legumes (e.g. cover crops) return the most nitrogen to the soil.
- Net nitrogen contribution varies by species and management, with some legumes resulting in a negative nitrogen balance if most biomass is exported.
- Harvesting legume products requires additional traffic, increasing the risk of soil compaction.
- Plan legume use and harvest timing with nitrogen cycling in mind, especially before high-demand crops.

Applying the science on-farm

In the world of farming, where growers are at the mercy of environmental factors, any clarity on actions that are within a grower's control will have a meaningful impact.

This section explores how growers can apply the science of legumes on-farm, with practical strategies and case study examples of how growers with varying systems have used legumes as a nitrogen source for their cash crops.

Before we begin, here is a quick recap of the objectives and important considerations.

Background

The goal

The objective is straightforward – use legumes to supply nitrogen to vegetable crops. However, achieving the matched release of nitrogen availability from legume residues with the nitrogen demand of the vegetable crop is complex.

Nitrogen dynamics are driven by biological processes that vary with weather, soil and time. As UK grower Toby Baxter said:

"You can't plan your way around nature. Nature will be nature."

And while this is true, there's still plenty we can influence, and that's where thoughtful management comes in.

Asynchrony: the risk of misalignment of nitrogen supply and demand

Crews and Peoples (2005) describe mismatches between nitrogen supply and crop demand as asynchrony, and it can go both ways:

Excess asynchrony: Too much nitrogen becomes available when crops do not need it. This nitrogen is vulnerable to loss (leaching, volatilisation) or can overstimulate the crop, causing weak, vegetative growth more prone to disease and lodging (Meena et al., 2017; Veromann et al., 2013; Huber et al., 2011) .

Insufficient asynchrony: Too little nitrogen is available when crops need it most, reducing yield and quality.

The aim is to minimise both. That means managing when and how nitrogen is made available, and tailoring practices to the farming system.

Tailor practices to the farming system

Environmental and biological factors differ by region, season and soil, so there is no one-size-fits-all approach. To get the most from legumes, growers need to align legume use with the specifics on their farm:

- Business goals and operational constraints
- Crop rotations (cash crops and cover crops)
- Time windows for legume growth and termination
- Climate (temperature, rainfall) and seasonality
- Soil type
- Machinery available for sowing and termination
- Crop nitrogen demand – when and how much is needed?
- Markets – will the legume be harvested for sale?
- Pest and disease risk in the crop sequence

As Dutch researcher Lennart Fuches put it

“Think about the system, and the relationships between each component”

Choosing how to grow legumes

Legumes can be integrated into vegetable systems in several ways, each with its own nitrogen contribution, management needs, benefits and considerations. The method chosen should match the goals, equipment and timing available on the farm. Examples of grower case studies and their approaches are summarised in Table 9, and follow in the subsequent sections.

Table 9: Summary of case studies and key approaches explored throughout this report.

Method of growing	Case Study	Key Feature
Cover cropping with legumes	Ed Lea (UK)	Green manure in mixed vegetables system
	Phil Bartolo (NSW, Australia)	Brown manure, strip till, mulching in cabbage production
	Mark Fritz (Qld, Australia)	Summer legumes, long-term cover cropping in rotation with potatoes
	Erwin Westers (Netherlands)	Cut and carry, biodynamic, mulch reuse
	Planty Organic (Netherlands)	Model driven, full legume nitrogen system
Companion cropping with legumes	Laurent (Woody) Van Arkle (Canada)	Living mulch clovers, strip-tilled, corn
	Laura Van Eerd (Canada)	Clover undersown in wheat before corn
	Lotte van Dueren den Hollander (Netherlands)	Companion cropping legumes in potatoes
	David Guy (France)	Organic, low-till, strip cropping and intercropping grains
Growing legumes as cash crops	Ken Giller (Africa)	Legume cash crops in Africa
	Sementes Com Vigor (Brazil)	Soybeans, systems thinking

Case studies: cover cropping with legumes

Cover cropping with legumes often offers the biggest ‘bang for your buck’ when it comes to contributing nitrogen with relatively low complexity.

The following case studies explore how growers in Australia, the UK, and the Netherlands are using legume cover crops to support nitrogen supply and improve soil health in vegetable systems. While their methods differ, from green manure incorporation to reduced tillage, cut-and-carry, and whole-system modelling, they each highlight practical strategies for working with, not against, the biology of nitrogen cycling.

Together, these examples show that there’s no one-size-fits-all approach. When managed well, legumes can play a central role in improving nitrogen efficiency, system resilience and overall soil function.

The growers, working across different climates, crops, and contexts, consistently recognised that nitrogen from legumes is not automatically available. While most did not measure nitrogen fixation, additions or availability directly, they relied on observation and experience. However, there is potential to refine the approach by using biomass cuts, soil and sap tests, or nitrogen modelling tools to time nitrogen release and guide fertiliser decisions.

Importantly, all growers actively managed nitrogen dynamics, tailoring their approach to their system. They used key levers to influence nitrogen availability from legumes to ensure it fit within the broader farm context. These practices are summarised in Table 10.

Table 10: Practices used by growers to influence nitrogen availability from legume cover crops.

Practice	Impact on nitrogen dynamics
Species selection	Chosen to suit business objectives, termination method, and rotation timing
Timing of termination	Later termination timing increased biomass and nitrogen influenced by season, termination method and the following crop.
Termination method and residue handling	Methods included both roller crimping, mulching, strip tillage, light incorporation, full incorporation and direct drilling – each affecting nitrogen release.
Moisture and temperature	Cold or dry soils slowed mineralisation, even with high biomass.
Cut and carry systems	Enabled controlled nitrogen reapplication and stimulated nitrogen fixation.
Further nitrogen applications	Used to supplement legume-derived nitrogen (e.g. with compost, manures, carbon-coated urea or traditional fertilisers).

One recurring challenge across sites was slug and snail pressure in high-residue systems. This was managed with slug baits, mowing and close monitoring, particularly where residue was retained on the surface.

Some growers were willing to accept slightly lower yields in exchange for fertiliser savings and a more resilient, biologically driven system. Others found ways to reduce costs through saving seed and using lower-cost inoculants like peat or liquid formulations.

What stood out across all sites was that flexibility and adaptability were key. The most successful systems evolved through trial and error, and were tailored to suit each farm’s specific climate, soil, equipment, and goals.

Key points:

- Cover cropping with legumes is a practical and cost-effective way to add and store nitrogen, improve soil structure, boost OM, and support weed and disease management.
- Nitrogen availability is not available straight away – it depends on factors like biomass, species, termination method, soil conditions, and timing relative to the cash crop.
- Most growers managed nitrogen using experience and observation, but there's potential to improve decision-making using tools like biomass assessments, soil/sap/ tissue tests, and nitrogen models.
- Cut and carry systems offer more control over nitrogen timing and placement but are generally better suited to high-value crops due to the additional handling costs.
- Common challenges included managing slug and snail pressure in high-residue systems, and timing termination to fit within vegetable planting schedules.
- Flexibility and adaptability were critical. Successful systems evolved through trial and error, and were tailored to suit local conditions, crop needs, and operational constraints.

Ed Lea, UK – integrating cover crops in a mixed vegetable and cereal system



Figures 7 to 9: (From L to R) Ed Lea standing in cover crop; cover crop with grasses and legumes; pumpkin growing on strip tilled and surface retained cover crop (Author, 2024).

Ed Lea is the farm operations manager at G's Fresh Produce, which operates across multiple regions under both organic and conventional systems. The team tailors their approach to each site, depending on crop requirements and access to inputs such as compost. Their diverse rotations include vegetables like pumpkins, salad onions, green beans, peas, and runner beans, along with cereals and a well-established cover crop phase every four years.

A notable innovation being considered is leaving strips of clover growing between slower-growing salad onions. Managed with an interrow flail mower, this approach aims to boost soil fertility and protect the soil surface, aligning with regenerative principles.

Their cover crop, referred to as a "fertility blend", includes grasses, legumes (such as vetch and clovers), linseed, and buckwheat. It is mown regularly to stimulate regrowth and build biomass, then incorporated into the soil prior to vegetable planting. This approach serves as a green manure and supports a multi-year crop sequence that builds soil health and productivity.

The team has also been trialling strip tillage, particularly ahead of green beans and pumpkins, using two passes: one in autumn and one before spring planting. While direct drilling was explored, it was not suited to their system. Strip tillage has shown promise, although residue management and slug pressure remain challenges, requiring careful use of baits.

While nitrogen contributions from legumes and cover crops are not directly measured, the team makes informed assumptions based on experience in organic systems, and adapts those learnings to conventional paddocks. This highlights the value of knowledge transfer between farming systems.

This case study illustrates the use of legumes as part of a green manure approach, tailored to both organic and conventional rotations. It also shows how reduced tillage, regular mowing, and adaptive residue management can be layered to support nitrogen contribution and broader soil function.

While Ed's system centres on green manure incorporation, the next case study – Phil Bartolo in NSW, shows how diverse cover crop termination approaches play a valuable role in both managing weeds and more effectively supplying nitrogen to brassica crops.

Phil Bartolo, NSW – reduced tillage and diverse cover crop termination approaches before brassicas





Figures 10 to 14: (From L to R, top to bottom) Phil Bartolo standing in mixed faba bean and oat cover crop; cover crop roller crimped (at termination); cover crop roller crimped (months after termination); strip rotary hoe; residues in the understory of cabbage crop (Author, 2024).

Phil Bartolo farms heavy clay soils with high organic matter (8.5–9.5%) that are well structured and biologically active, abundant with earthworms. Within his cabbage production system, Phil has been experimenting with cover crops and reduced tillage to improve soil function while maintaining productivity.

Cabbage is the main cash crop, typically grown from winter through to summer. Between brassica crops, Phil has trialled a range of cool and warm season cover crops, including oats and faba beans in winter, and millet and sunflowers in summer. Legumes such as faba beans are inoculated to encourage nodulation and biological nitrogen fixation.

Rather than adopting a single approach, Phil has experimented with different establishment and management methods to suit seasonal conditions. Cover crops have been established both by broadcasting seed and by direct drilling. Direct drilling has generally provided more consistent establishment, while broadcasting can reduce sowing times.

Soil preparation has also been an area of experimentation. Historically, the system involved deep ripping followed by multiple rotary hoe passes. More recently, Phil has trialled forming beds and ripping prior to cover cropping to minimise disturbance after the cover crop phase. In other situations, soil preparation occurs after the cover crop to provide an effective “reset” before cabbage planting. These approaches reflect a balance between retaining the benefits of cover crop residues and maintaining drainage and workable soil structure in heavy clay soils.

Phil has also explored different implements and levels of disturbance for bed preparation following cover crops, including a rotary hoe, speed disc and modified strip rotary hoe. The strip rotary hoe, originally designed for inter-row weed control, has been repurposed to create narrow tilled strips through retained mulch ahead of transplanting. This allows cabbage seedlings to be established while maintaining surface residues between rows, reducing soil disturbance, fuel use and time.

Termination methods vary depending on objectives. In some cases, cover crops are roller-crimped at flowering and left on the soil surface as brown manure, providing longer-term ground cover to protect soil from erosion and suppress weeds. Alternatively, crops are mulched or incorporated to accelerate residue breakdown and allow faster nutrient cycling when paddock turnaround is required.

Phil's experiments have provided useful insights into how residue management affects nitrogen availability from legume cover crops. When legume-containing cover crops were roller-crimped and residues retained on the surface for extended periods (around six months), nitrogen was released slowly over time. By the time the next cabbage crop was established, much of the nitrogen fixed by the legumes was no longer readily available to the crop.

Mulching and incorporating residues closer to planting increased soil nitrogen availability, although timing proved critical. Early trial results showed that incorporating residues only two weeks before planting in cooler months did not allow sufficient time for nitrogen mineralisation. Extending the interval between mulching and planting to around eight weeks resulted in higher levels of plant-available nitrogen prior to cabbage establishment.

These observations highlight the importance of aligning residue management and timing with crop nitrogen demand. While legume cover crops can contribute nitrogen to the system, the way residues are managed strongly influences how much becomes available to the following crop.

Phil is considering these learnings and how fertiliser nitrogen inputs could be reduced in some situations. However, he remains cautious about reducing base fertiliser rates too aggressively due to the risk of wet conditions preventing timely side-dress applications.

Phil's experience demonstrates a practical, adaptive approach to integrating cover crops and legumes into intensive vegetable systems. Rather than relying on a fixed system, he continues to adjust species selection, residue management and cultivation practices in response to seasonal conditions and emerging on-farm learnings.

In the next case, Mark Fritz in Queensland, shows how summer legumes in hot climates can reduce synthetic nitrogen use in potatoes, while building long-term soil resilience.

Mark Fritz, Queensland – summer legumes and long-term cover cropping in potatoes

Figures 15 to 17: (From L to R) Sunn hemp cover crop at flowering; sunn hemp cover crop terminated by mulching; Mark Fritz (left with his farm team) standing in mulched sunn hemp residue months after termination (Author, 2025).

Mark Fritz, along with his son and farm team, grows processing potatoes in Queensland on a two-year cycle, planting in April and harvesting in September. For over 20 years, Mark has been refining a cover cropping system to improve soil structure, manage disease, and reduce reliance on synthetic inputs.

His program includes winter cereals (triticale, barley, cereal rye) and summer legumes like cowpea and sunn hemp. These legumes are valued not only for nitrogen fixation, but also for weed suppression (via selective spraying) and pest management, particularly sunn hemp, which helps reduce fall armyworm pressure.

The system is low-till and highly practical. Cover crops are sown immediately after harvest using basic equipment like spreaders, disc drills, or a speed tiller with a seeder box, to capitalise on residual soil moisture. Irrigation is not used, so timing is critical.

Termination is tailored by species:

- Sunn hemp is mulched and left as surface residue at flowering.
- Cowpea is crimped and side-mowed.
- Sorghum is mown multiple times throughout its growth.

In all cases, residues are retained on the surface to build OM and feed soil biology, rather than being fully incorporated.

While nitrogen contribution is not formally measured, legume use has enabled Mark to reduce fertiliser nitrogen by 40 kg/ha in potatoes. He complements this with carbon-coated urea for a slower nutrient release and uses basic soil testing to track OM and nutrient levels across paddocks.

Cost is a key consideration. Inoculated legume seed can cost up to $600/ha, but Mark saves his own seed, is experimenting with lower-cost inoculants, and fine-tuning seed rates to maximise weed suppression.

Challenges include weed management (especially volunteer potatoes), variable establishment in dry years, and pest pressure. Still, yield improvements from 32 t/ha to 40 t/ha, reduced disease pressure (e.g., powdery scab, verticillium), and improved soil health have validated the long-term investment.

Mark's advice:

"Start small, be willing to experiment, and adapt to your own conditions.
Even if it's not perfect, it's better than not trying at all."

While Mark's system shows how legumes can support nitrogen reduction in a warm, low-input potato system, the next case study, Erwin Westers in the Netherlands adopts a cut and carry approach that brings many benefits and improved yields in his potato crop.

Erwin Westers, Netherlands – recycling cover crop biomass to improve potato performance

Figure 18 to 23: (From L to R, top to bottom) mixed cover crop paddock; mixed cover crop close up showing inclusion of legumes (Author, 2024); Erwin Westers standing in rye and vetch cover crop at flowering; rye and vetch cover crop being mulched and harvested; Erwin standing in front of tractor spreading rye and vetch cover crop over potatoes; rye and vetch cover crop mulch on germinated potatoes (Bij de Oorsprong, 2024).

Farming on reclaimed land in the Netherlands, Erwin Westers integrates diverse cover cropping into a system producing carrots, salad crops, seed potatoes, and peas. A standout feature is the strategic cut and carry practice, where cover crop biomass is harvested and reapplied as mulch on potato crops to improve resilience and soil biology.

The process begins with a cereal rye and vetch cover crop grown to flowering, then cut and spread as a seven-centimetre-thick mulch over germinating potatoes. This mulch:

- Retains soil moisture during dry periods
- Moderates soil temperature through shading
- Suppresses pests and disease, such as Colorado beetle and late blight
- Prevents erosion from rainfall impact
- Improves yield – increases of 30–50% have been observed

Unlike incorporated residues, this approach promotes slower decomposition and supports soil microbial activity in the upper layers where early plant roots interact.

Erwin's broader system is rooted in regenerative and biodynamic principles, aiming to maximise photosynthetic energy capture and internal nutrient cycling. Cover crop mixes (20-30 species annually) are designed to balance:

- Carbon (grasses/cereals)
- Nitrogen (legumes)
- Secondary metabolites (herbs)

Key design features include:

- Cover crops under-sown into seed crops, requiring careful management
- Minimal tillage and controlled traffic
- Farm-made biologicals (Johnson-Su compost, plant ferments, and compost teas)
- Monitoring tools (sap testing, fungi:bacteria ratios and Brix-level)
- Rotation planning to enhance diversity

Erwin also removed animals from the system, relying instead on plant-based nutrient cycling and soil biology. His approach is guided by the principle of

"Not controlling, but organising and designing the system."

This case study shows the diverse benefits of cut-and-carry approaches, however, the cost and logistics of biomass handling mean it's best suited to high-value crops like potatoes.

Erwin's system rethinks how and where cover crop nitrogen is applied, while the next case study, Planty Organic, takes this a step further, showing how a legume-only nitrogen system can be managed without synthetic or animal inputs, guided by nitrogen modelling tools.

Planty Organic, Netherlands – legume-only nitrogen strategy in organic vegetables

Figures 24 to 27: (From L to R, top to bottom) clover ley; silage clover; carrots with clover silage applied; pumpkins with clover silage applied (Author, 2024).

The “Planty Organic” project, running since 2012 in the Netherlands, demonstrates how arable vegetable systems can run entirely on legume-derived nitrogen without synthetic fertilisers or animal manures.

While the system demonstrated clear benefits for nitrogen management, broader nutrient dynamics were also monitored. Phosphorus levels remained stable, likely due to existing high soil reserves, however a decline in plant-available potassium was noted. This is of relevance given potassium’s role in supporting nitrogen fixation in legumes. This warrants consideration when managing nutrient inputs in similar systems (Van Der Burgt et al., 2021).

The study addresses a key inefficiency in many organic systems, where grass-clover leys are sold to livestock farms, then returned as manure, often with up to 40% nitrogen lost in the cycle.

Instead, Planty Organic uses a cut-and-carry approach:

- Pure clover species (lucerne, red, white, and Alexandrian) are grown for 1.5 years and cut 3-4 times.
- Biomass is ensiled at 30-40% dry matter, preserving nitrogen with minimal losses (~3%).
- Silage is reapplied and incorporated into the soil in February-March in the three paddocks that will have crops with the highest nitrogen demand.

This allows:

- Precise timing and placement of nitrogen release, knowing the relatively slow-release pattern of nitrogen from the cut and carry fertiliser

- Improved nitrogen use efficiency, as the nitrogen remains in organic form until mineralised
- Enhanced fixation, since repeated cutting stimulates legume regrowth and continued nitrogen fixation

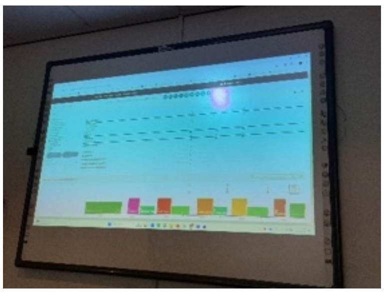
To enable this, the team made several system-level changes:

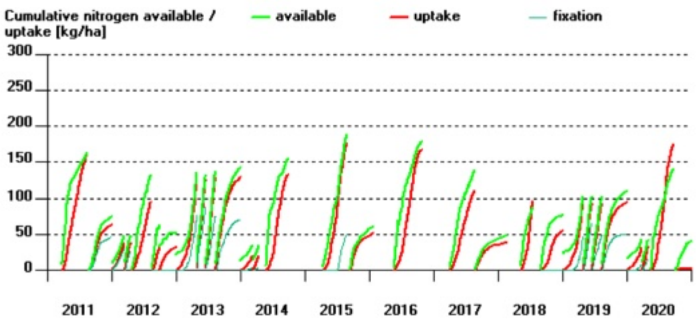
- Switching grass-clover leys with pure clover (easier to manage, slightly lower biomass)
- Adopting diverse rotations (pumpkin, carrot, potato, wheat, fodder radish, oat/vetch green manures)
- Used thermal weeding for organic weed control (requires precise timing and favourable weather)

Key outcomes:

- Yields were lower than conventional or compost-based organics
- NO_3^- leaching was minimal
- Stable OM levels
- High nitrogen use efficiency
- Spring crops had greater nitrogen shortfalls due to mineralisation in cold soils

NDICEA: Modelling nitrogen availability





Figures 28 & 29: (From L to R) NDICEA model output showing cash crop uptake; NDICEA model output showing nitrogen 'available' from mineralisation of legumes, and 'uptake' by the vegetable crop (Geert-Jan van der Burgt, 2024).

To support nutrient management, the trial team used the Nitrogen Dynamics In Crop rotations in Ecological Agriculture (NDICEA) tool (www.ndicea.nl), which simulates:

- Mineralisation of organic nitrogen over time
- Losses (leaching, volatilisation, and denitrification)
- Interactions between weather, crop uptake, and biomass inputs

Originally designed for research and education, NDICEA is increasingly relevant as a planning tool for

- Low-input growers, seeking to synchronise legume nitrogen with crop needs, and
- Conventional growers confronted with challenging environmental (nitrogen) targets.

This case study shows how nitrogen from legumes can be captured, stored, and released entirely within a closed-loop system, supported by modelling and strategic management. Though labour-intensive and lower yielding, it is a leading example for growers pursuing full input independence, particularly in high-value organic vegetable systems.

Wrap up

These case studies illustrate that while legumes offer significant nitrogen potential, their real strength lies in how they fit into broader system goals, from reducing inputs and managing disease, to improving soil biology and operational efficiency. The most effective outcomes came from growers who tested, observed, and adapted, proving that even without perfect conditions, progress is possible through persistence and learning.

Case studies: companion cropping with legumes

Companion cropping with legumes offers a promising yet more complex opportunity to integrate biologically fixed nitrogen into vegetable systems. Unlike cover cropping, where legumes are grown before or after the cash crop, companion systems involve growing legumes alongside the main crop – in the same space, at the same time.

In vegetable systems, where crops are often short-season, intensively managed, and sensitive to nutrient imbalances, companion legumes must be chosen and managed with care. Success lies not in simply adding legumes, but in designing systems where they complement rather than compete with the cash crop.

The following four case studies explore different companion cropping approaches across broadacre and vegetable contexts in Canada, the Netherlands and France. They include strip tillage into perennial legumes; undersowing legumes into cash crops; simultaneous planting of cash crops with legumes; and strip cropping and intercropping in organic no-till systems.

While the cropping systems differ, several common principles emerged:

- Legumes were chosen for compatibility with the cash crop, aiming to reduce competition.
- Spatial separation and mowing were used to manage growth and stimulate nitrogen cycling.
- Benefits were system-wide, including improved crop quality, weed suppression, or soil biology, even where direct nitrogen contribution was hard to quantify

These systems were not one-size-fits-all. Each evolved through observation and adaptation, requiring growers to tailor their approaches to their own rotations, equipment and climate. For vegetable growers, this adaptability is critical. Table 11 summarises key practices used by growers to influence nitrogen dynamics from companion legumes.

Table 11: Practices used by growers to influence nitrogen availability from companion legumes.

Practice	Impact on nitrogen dynamics
Species selection	Choosing legumes with compatible growth habits (e.g., low-growing vs. vigorous climbers) to reduce competition and improve co-existence with vegetables.
Spatial arrangement	Use of strip tillage, sprayed out bands, or interrow planting to separate legumes and cash crops, reducing competition and enabling targeted management.
Mowing	Stimulating root sloughing and nitrogen release. Timing and frequency affect mineralisation and soil cover.
Termination method	Incorporation accelerates mineralisation, while no-till or herbicide termination slows release but preserves soil structure. Balance is required to retain soil health and crop needs.
Timing of cover crop termination	Aligning legume termination with peak nitrogen demand of the cash crop improves synchrony and nitrogen use efficiency.

As with cover cropping, companion systems also came with trade-offs:

- Quantifying the nitrogen benefit is challenging. Unlike cover crops, companion legumes often contribute nitrogen through subtler pathways like

rhizodeposition, root turnover, and microbial stimulation. Nitrogen contribution is often indirect, delayed, and context-specific.
- Managing competition is crucial. Legumes can compete with vegetables for light, water, and nutrients, particularly in early growth. Species choice, strip width, and management practices are key to avoid negative interactions.
- Pest and disease dynamics are unpredictable. Some systems supported beneficial insects and reduced weeds, while others faced new challenges such as slugs or disease carryover in high-residue environments.
- Operational complexity increases. Companion cropping adds layers of decision-making to planting and termination, often requiring more tailored equipment or sequencing.

Despite these challenges, the growers observed broader system benefits and at least partial reductions in fertiliser use. Their systems were dynamic and iterative, designed to evolve with observation, experience and changing conditions.

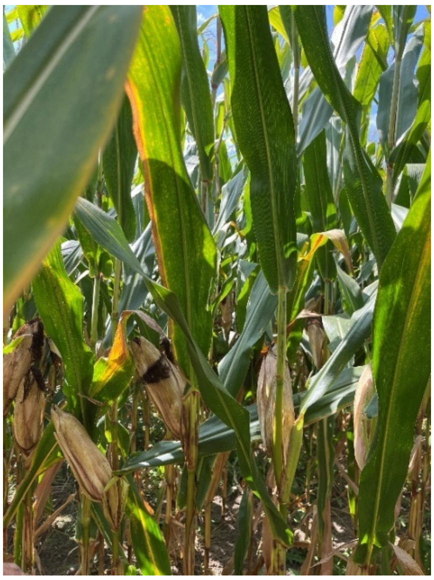
Key points:

- Companion cropping with legumes involves growing legumes within the same space and time as the cash crop.
- Key levers include species choice, spatial separation, mowing, and termination timing and method.
- Nitrogen contributions are difficult to measure, but benefits often occur through biological stimulation.
- Companion systems can support reduced inputs, better weed management, improved soil biology, and more resilient rotations, but require thoughtful design and adaptability.
- Vegetable growers need to tailor these concepts, but the underlying principles remain transferable.

Laurent (Woody) Van Arkle, Canada – clovers as a living mulch in corn for nitrogen cycling and soil health






Figures 30 to 37: (From L to R, top to bottom) maize corn with clovers in the interrow; example of clover biomass before termination and planting corn; collage of planting corn in strip tilled clover including Woody inspecting the clover companion crop; treatment without clover and no nitrogen applied; treatment with clover and no nitrogen applied; strip mower planter that woody built (Author, 2024).

Woody Van Arkle has been trialling perennial clovers as a living mulch in a strip-tilled corn system. His goals are to reduce tillage, improve soil health, suppress weeds, and explore nitrogen contributions through root interactions and residue cycling.

A mix of white clover and subterranean clover was sown at 10 kg/ha, forming a semi-permanent cover. This cover aimed to be self-seeding and low maintenance, providing year-round ground cover, with a living root system to feed soil biology and store nutrients. Corn is then direct-drilled into 8-14 inch sprayed-out bands (glyphosate and Lontrel) within the clover, following autumn strip tillage. The band width has proven critical – too narrow, and the clover outcompetes the corn; too wide and soil coverage and weed suppression are lost.

Woody conducted a trial comparing four treatments:

1. Corn, clover and 135 kg N/ha
2. Corn, clover and no added N
3. Corn, no clover and 135 kg N/ha
4. Corn, no clover and no added N

These comparisons aimed to assess whether the clover can provide nitrogen or other benefits under lower input systems. Early observations showed corn grown with clover but without nitrogen remained greener for longer (Treatment 2, Figure 33) than corn grown without either clover or nitrogen (Treatment 4, Figure 34).

This was also reflected in yield – corn with clover but no added nitrogen (Treatment 2) outyielded corn with neither clover nor nitrogen (Treatment 4), and performed comparably to corn grown with clover and full nitrogen inputs (Treatment 1) (Figure 38). This suggests some nitrogen cycling is occurring, possibly via root turnover or residue breakdown, though the mechanism remains unclear.

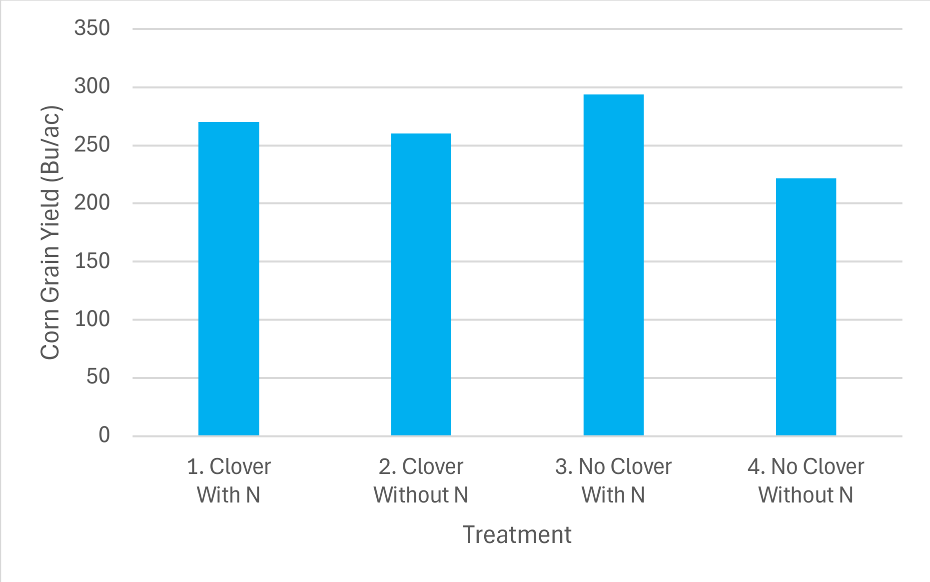


Figure 38: Corn yield from trial conducted on Woody's farm.

Woody is particularly interested in how mowing, shading, and root senescence influence nitrogen release. Mowing is thought to stimulate root sloughing (when some roots die off), feeding soil microbes and increasing mineralisable nitrogen. While research has been inconclusive on the degree of nitrogen sharing between legumes and non-legumes, Woody's observations show some interaction, with potentially delayed benefits.

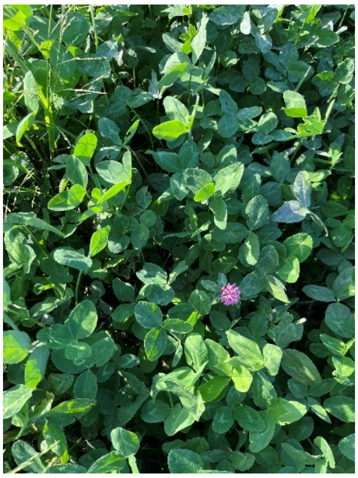
Monitoring has also included soil biology assessments, including arbuscular mycorrhizal fungi, beneficials, and pathogens. Samples have been collected before planting, during crop growth, and post-harvest. Ammonium, organic nitrogen, and plant-available phosphorus have also been measured in the clover interrows compared to bare ones.

This living mulch system is also reducing herbicide use through weed suppression, though species choice is critical. White clover in particular is highly competitive during crop establishment if not managed carefully, and can be difficult to terminate.

While nitrogen contributions remain difficult to quantify, Woody is committed to refining the system and uncovering how perennial legume companions can support nutrient cycling, weed suppression, and soil resilience in low-input corn systems.

His work highlights the potential of integrating legumes within the cash crop phase but also raises questions about how timing and crop sequencing might further improve nitrogen synchrony. One approach gaining traction is to introduce legume companion cropping before the main crop, an idea explored in the next case study by Canadian researcher Laura Van Eerd.

Laura Van Eerd, Canada – undersowing clover in wheat for corn nitrogen benefit

Figures 39 & 40: (From L to R) Clover sown in wheat; close up of clover biomass at the Ontario Crop Research Centre in Ridgetown (Author, 2024).

Laura van Eerd is exploring the use of undersown clovers in winter wheat to supply nitrogen to the following corn crop, reduce fertiliser inputs, and maintain flexibility when weather limits side-dress opportunities.

Clover seed (typically red clover) is broadcast over winter wheat in early spring (March/April), then naturally worked into the soil through freeze-thaw cycles, a method backed by local research (Grigg et al., 2021). After wheat harvest in July, the clover continues growing, forming a green bridge through summer and autumn.

If the post-harvest clover stand is patchy, legumes such as forage peas or crimson clover are reseeded. The clover is mowed to manage weeds and stimulate regrowth but isn't typically needed. Termination occurs either in late autumn or the following spring, via tillage or herbicide, depending on soil or crop needs.

The clover contributes around 45-90 kg N/ha to the subsequent corn crop, depending on clover density and termination method. Incorporation via tillage typically releases more nitrogen than no-till termination. The clover's nitrogen release aligns with corn's peak demand in June to July, improving synchrony between nitrogen availability and crop uptake.

While some growers have credited clover with saving 55 kg N/ha, research suggests 70+ kg N/ha, others remain cautious. Synthetic nitrogen is still seen as cheap insurance to safeguard yields, especially when wet spring conditions make side-dressing difficult.

A key challenge noted in no-till systems is the potential for slug damage. Decisions around tillage, termination timing, and residue management must therefore balance pest risks with soil and nutrient benefits.

This system reflects a practical, low-disruption way to integrate legumes into the rotation. It highlights how intermediate cover phases can deliver nitrogen without disrupting the cash crop sequence. Building on this idea, Lotte van Dueren den Hollander takes the concept a step further, companion planting legumes within the vegetable crop itself to reduce nitrogen inputs and enhance crop performance, even in high-value, high-regulation systems like potatoes.

Read more about interseeding clover in wheat to increase corn yields and the economics here https://soilsatguelph.ca/crop-rotation-counts/ and here www.qualityseeds.ca/using-red-clover-in-wheat-to-increase-corn-yields/.

Lotte van Dueren den Hollander, Netherlands – companion cropping in potatoes for reduced nitrogen

Figures 41 to 43: (From L to R) Potatoes intercropped with companion crop containing legumes; close up of companion crop in potato hill; potato roots and tubers at time of visiting (Author, 2024).

Lotte van Dueren den Hollander and her father are applying companion cropping within potato ridges to reduce nitrogen inputs and farm more in tune with nature. The system involves co-planting vetch, buckwheat, and flax alongside potatoes to attract beneficial insects, suppress weeds, and potentially reduce fertiliser needs through enhanced biological interactions.

Planted at the same time as the potatoes, the companions grow within the ridge line, while mechanical weeders manage the interrow. The cover crop typically freezes off over winter or is mown and incorporated if not.

Key outcomes observed include:

- 23% reduction in N fertiliser, with no yield penalty
- Improved tuber size and quality
- Lower herbicide use due to competitive groundcover

Lotte suspects some nitrogen sharing or stimulation of soil microbes, possibly via mycorrhizal interactions, though this is still being explored.

This system aligns with broader goals of reduced tillage, biodiversity enhancement, and precision input use, showing how companion species can deliver multiple benefits while maintaining productivity in a regulated and rotation-conscious potato system.

While Lotte's approach demonstrates how companion species can function within a single crop to enhance performance and reduce inputs, David Guy takes the concept further, combining intercropping, strip cropping, and cover crop management within a fully organic, no-till system. His experience reveals how legume integration can support nitrogen cycling as part of a broader, whole-of-system strategy.

David Guy, France – organic no-till strip cropping and intercropping for soil health and nitrogen management



Figures 44 to 46: (From L to R) Strip cropping sunflowers with mixed cover crop in between strips; grains harvested after crops grown as intercrops; screens used to separate grain harvested when intercropped (Author, 2024).

Farm owner David Guy adopted no-till on his farm in 2002, and transitioned to organic no-till farming in 2017. During the organic transition, David embraced strip cropping and intercropping as core strategies for building soil health, managing weeds without herbicides, and fertilising without synthetic inputs.

His diverse cover crop mixes, including mustard, phacelia, oats, vetch, radish, sunflower, field bean, sorghum, buckwheat and flax, are strategically grown between winter and summer crops like wheat, barley, peas, and sunflowers. These covers are mulched or lightly incorporated to stimulate nitrogen mineralisation, suppress weeds, prevent erosion and break disease cycles.

Strip cropping is used with staggered plantings to maintain continuous green cover and support beneficial organisms. While some strips contain the same crop for operational ease, others combine multiple species to enhance biodiversity and soil function.

As nitrogen supply through synthetic fertilisers is not an option in organic farming systems, David embraced intercropping with compatible cash crops of legumes and cereals. The crops are grown together, harvested simultaneously and the grain is separated using different sized screens. Compatible intercrops included lupin with wheat, field bean with triticale, and field pea with barley. Key learnings highlight the importance of seed size, growth compatibility, and matched maturity to minimise competition and lodging.

Nitrogen management follows a “bilan azote” (nitrogen balance) approach, informed by soil testing to estimate mineralisable nitrogen and crop uptake. High C:N cover crops require timely termination, often through shallow cultivation, to speed up mineralisation and avoid temporary immobilisation.

David’s system highlights how legume integration, when paired with thoughtful spatial and temporal design, can support organic nitrogen cycling while maintaining productivity in complex, biologically rich cropping systems.

Wrap up

These four case studies demonstrate the diverse ways legumes can be used as companion crops; from perennial clovers in strip-tilled corn, to undersown legumes in cereals, to in-ridge mixes in potatoes, and complex intercropping in organic systems.

While cropping contexts varied, each example shows how careful design, through compatible species, spatial strategies and timing, can help companion legumes support nitrogen cycling and broader system performance. For vegetable growers looking to diversify their rotations and reduce fertiliser use, these case studies offer practical, adaptable ideas that can be trialled and refined to suit different farming systems and goals.

Case studies: growing legumes as cash crops

Growing legumes as cash crops presents a valuable opportunity to reduce fertiliser use while generating income, particularly where legumes are managed for both yield and nitrogen fixation.

Unlike cover cropping or companion systems, cash crop legumes are harvested in some form, often fitting easily into crop rotations and requiring less complexity than cover and companion crops. However, to unlock their full potential as a nitrogen source, they need to be treated not just as a commodity crop, but as a key component of the farm's nutrient strategy.

The growers featured in the following case studies integrated legumes such as soybeans and pasture vetch into diverse farming systems that included grains, livestock, and cover crops. These legumes were not used passively; they were carefully managed with inoculation, nutrition, and rotational placement in mind, supported by agronomic practices that encouraged nitrogen fixation and nitrogen cycling. When done well, these approaches improved the performance of subsequent crops.

The benefits obtained from legume cash crops were more than just biological nitrogen additions. They delivered a marketable yield while also contributing to improved soil structure, increased biological activity, and better rotational diversity. Their integration often simplified management compared to cover or companion cropping systems, and their nitrogen contribution, even when modest, was enough to improve the performance of high-demand crops like maize or vegetables in the following rotation.

However, successful and optimal nitrogen fixation was not always certain; it varied depending on species, inoculation success, and soil constraints. Many commercially available legume varieties are bred for yield or disease resistance, not fixation efficiency. As a result, growers were often reluctant to reduce fertiliser inputs due to uncertainty around how much nitrogen was actually fixed and available to the next crop. Monitoring tools to quantify these contributions remain limited, making it difficult to adjust nutrient programs with confidence.

The growers who saw success focused on doing the basics well. This included approaches like inoculating seed, correcting pH, supplying phosphorus when there were deficiencies, and growing legumes before nitrogen-hungry crops. They also recognised that nitrogen fixation was just one part of a broader system benefit, with legumes contributing to soil health, structure, and overall productivity.

The following case studies demonstrate how legume cash crops can deliver these outcomes when treated with the same care and attention as any other key enterprise. The practices used to support nitrogen fixation and cycling are summarised in Table 12 below.

Table 12: Practices used by growers to influence nitrogen outcomes from legume cash crops.

Practice	Effect on nitrogen dynamics
Soil amendments like lime	Maintains pH conducive to rhizobial survival and activity.
Inoculation with rhizobia	Boosts fixation rates and improves nodulation and crop yield.
Co-inoculation with native bacteria	Enhances fixation (e.g. Rhizobium and Azosperillum in Brazil), reduces fertiliser requirements.

Crop nutrition	Supplying key nutrients to ensure successful nodulation and plant growth.
Crop sequencing (e.g. soybeans > corn)	Maximise carryover of nitrogen to high-demand crops.
Including legumes in pasture mixes	Supports nitrogen cycling and improves nitrogen retention across the system.
Whole-of-system focus	Emphasises rotational benefits, residue handling and integration with livestock for long-term cycling.

Key points:

- Legumes grown as cash crops can fix large amounts of nitrogen (often 30–100 kg N/ha), but only if supported with good management.
- Inoculation, legume nutrition, and pH correction are essential to achieving consistent fixation.
- Legumes that serve multiple purposes (e.g. income, biomass, pasture) are more likely to be prioritised and managed well, and can provide residual nitrogen for the next crop, even where synthetic fertiliser use is maintained.
- Vegetable systems can apply these lessons by selecting suitable legumes, managing them for both yield and fixation, and placing them before high-demand crops like corn, brassicas, or leafy greens.
- Legume cash crops may offer a simpler alternative to cover cropping in some systems, provided markets and harvesting capacity exist.

Ken Giller, Africa – N2Africa scaling up nitrogen fixation in legume cash crops

Figures 47 & 48: (From L to R) Local women inspecting soybean crop; professor Ken Giller in legume crop (Ken Giller, year unknown).

The N2Africa project, led by Professor Ken Giller from Wageningen University, Netherlands, was a major initiative designed to support smallholder farmers across sub-Saharan Africa in using legumes more effectively as both crops for food or sale and biological nitrogen sources.

Operating in eleven countries, the project focused on key legume species such as common bean, cowpea, groundnut, and soybean, all widely grown on the continent but often underperforming in terms of nitrogen fixation.

A key aim of the project was to shift legumes from being passive rotational crops to active nitrogen contributors. It also worked from the premise that biological nitrogen fixation effectiveness results from the interaction of legume and rhizobial genetics, environment, and management. To do this, the team promoted several practical interventions:

- Inoculating seeds with rhizobia, particularly for soybean, which often lacked compatible native strains
- Correcting phosphorus deficiencies, which were a major limiting factor for nodulation and fixation
- Encouraging basic agronomic practices, such as early sowing and correct row spacing
- Supporting market development to ensure farmers had a financial incentive to grow legumes at scale

The results showed well-managed soybean crops fixed up to 250 kg N/ha/year. In farmer trials, the combination of inoculation and phosphorus fertiliser increased soybean yields from less than 1 t/ha to over 3.5 t/ha. Importantly, many growers observed a yield lift in subsequent maize crops, even where fertiliser rates were reduced, a clear sign of residual nitrogen benefit.

Yet, adoption was not immediate. Across regions, legumes typically occupied less than 10% of total cropping area. Where legumes succeeded, it was because they delivered multiple benefits: income, fodder, food security, and soil fertility. This whole-of-system value made them worth investing in, even in smallholder contexts.

This case study shows that, under the right conditions, legumes as food and cash crops can contribute substantial amounts of nitrogen to farming systems, but only when the fundamentals are done well.

For growers elsewhere, including in vegetable systems, the same principles apply: match the right species to the system, inoculate where appropriate, and do not overlook the role of key nutrients like phosphorus in unlocking nitrogen fixation. Where these elements align, legumes can reduce fertiliser needs and support the following crop, particularly high-demand ones like vegetables.

The next case study, from Brazil, illustrates how these principles can be integrated at a whole-farm level, with legumes playing multiple roles across diverse rotations to support both productivity and biological nitrogen cycling.

Sementes Com Vigor, Brazil – soybeans and systems thinking for nitrogen cycling



Figures 49 to 51: (From L to R) Peter from Sementes Com Vigor standing in soybean crop; soybean plant pods; soybean seeds inoculated with rhizobia and azospirillum (Author, 2024).

Sementes Com Vigor is a Brazilian family-owned operation integrating seed production, cash cropping, livestock, and cover crops within a diverse rotation. Their approach exemplifies how legumes, especially soybeans, can contribute to nitrogen cycling when managed intentionally across the whole farming system.

The farm runs two crops per year, with the following rotations:

- Corn > pasture
- Barley > soybean
- Pasture (rye, oats, hairy vetch) > corn
- Oats > black beans
- Wheat > soybean

Soybeans are a cornerstone of the rotation. Like 80% of other Brazilian growers, they inoculate seed at sowing but go a step further by using co-inoculation with Rhizobium and Azospirillum, a native nitrogen-fixing bacterium. Trials are underway to optimise the Rhizobium:Azospirillum ratio (typically 3:1) and fine-tune fertiliser rates to avoid overstimulating vegetative growth. Lime is also applied to maintain soil pH within the optimal range for rhizobia activity.

While soybean residues are estimated to contribute around 30 kg N/ha to the following crop, the real strength of the system lies in how legumes are managed across the rotation. Whether as cash crops, pasture components, or cover crops, legumes are treated with the same attention to nutrition, weed control, and soil structure as primary crops, reinforcing their value beyond just nitrogen.

In one example, a mixed rye–oat–vetch pasture is grazed by cattle to cycle nutrients and build structure. Before corn planting, grasses are terminated with herbicide, while the vetch is rolled down to form a mulch layer, allowing the grower to reduce synthetic nitrogen without compromising productivity.

Other adopted practices include:

- Cover crops (buckwheat, flax, peas, radish) between cash crops
- Reduced tillage and high residue retention
- Soil biology monitoring, with an emphasis on fungi–bacteria balance

By weaving legumes through multiple points in the rotation, as seed crops, pasture, and cover crops, this farm demonstrates how nitrogen can be built and cycled biologically, while still supporting profitable, productive agriculture. The lessons around inoculation, pH management, residue handling, and seeing legumes as system components, not just nutrient sources, are directly applicable to vegetable systems aiming to reduce input reliance.

Wrap up

These case studies demonstrate that when legumes are grown as cash crops with nitrogen in mind, they can offer much more than just a harvestable yield. With attention to inoculation, soil pH, nutrition, and rotation design, legumes can contribute meaningful amounts of nitrogen to farming systems and other indirect benefits to the broader rotation.

Growing legumes as cash crops however, can come with some trade-offs. The extent to which nitrogen benefits the following crop depends on how the legume is managed and how much is removed. Grain legumes often export a significant portion of the nitrogen they fix, limiting their residual contribution.

In addition, harvesting legumes for hay or grain requires additional farm traffic, increasing the risk of soil compaction, particularly in wet conditions. This can undermine the very soil health benefits that legumes are intended to support and should be factored into rotation planning.

Legume crops can still play an important role in supporting broader system outcomes, including income diversification, improved soil structure, rotational diversity, and biological activity. For vegetable growers, this highlights the value of integrating legumes not just as nutrient sources, but as part of a more resilient and biologically active system.

Management practices to maximise nitrogen fixation and manipulate nitrogen availability from legumes

Integrating legumes into vegetable systems offers a renewable, cost-effective source of nitrogen while improving soil health, biodiversity, and system resilience. However, to fully realise these benefits, especially aligning nitrogen release with crop demand, active and informed management is essential.

Drawing on the global case studies of legume use in cover, companion, and cash cropping scenarios, this section summarises practical management strategies for vegetable growers. As Geert-Jan van der Burgt put it:

"Using legumes effectively is a balance between science/ testing,
and gut feel/ nature".

Choosing the right legume

Legume selection should be based on regional climate, cropping window, soil type, and overall farm goals. Each species varies in its ability to fix nitrogen and suit different management approaches.

As demonstrated in the case studies, the intended use as cover crops, companion crops, or cash crops should guide species choice. Consider the legume's growth habit, ease of management, compatibility with rotation, and its broader role in the system, see Table 13 for examples.

While commercial data on native Australian legumes is limited, genera including Canavalia, Crotalaria, Cullen, Desmodium, Glycine, Kennedia, and Vigna, contain herbaceous species well adapted to local soils and low-input conditions (Bell et al., 2011). However, access to seed remains a key limitation.

Growth habit also influences lignin and polyphenol content. Upright legumes with woody stems break down more slowly than soft, herbaceous types. Choosing the right habit can influence how quickly nitrogen becomes available post-termination.

Table 13: Legume growth habits, examples, pros and cons.

Legume Growth Habit	Example species	Pros	Cons	Use case
Spreading, ground covers	Clover, Medic, Lucerne, Serradella	Erosion control, interrow cover, weed suppression, perennial or annual options	Can be hard-seeded and difficult to terminate; potential crop competition	Companion cropping, living mulches
Upright	Soybean, Faba Bean, Lentil, Chickpea	Easy to harvest and terminate, fits well in rotations, established inoculant practices	Generally lower biomass; lower nitrogen fixation under stress or poor inoculation	Cash crops, green manure

Vine	Field Pea, Vetch, Cowpea, Lablab	Dense biomass, good ground cover, high N fixation	Can interfere with mechanised operations; may need structural support	Cover crops, intercropping
Bushy	Pigeon Pea, Lupin, Common Bean	Moderate biomass, some weed suppression	May lodge; spacing management needed	Cash crops, rotation crops
Woody	Leucaena, Sesbania, Acacia, Gliricidia	Long-term fertility, shade, deep nutrient cycling	Slow to establish; unsuited to short rotations	Agroforestry, windbreak barriers, fodder systems

Grow the legume crop well and inoculate with rhizobia

Once the right species is chosen, focus on the basics: timely sowing, good establishment, appropriate nutrition, and inoculation with the correct rhizobia. Inoculation is a low-cost, high-return practice that significantly improves nitrogen fixation. Soil pH should also be checked, as acidic conditions can limit rhizobia activity.

Timing of planting

Sowing date influences legume growth, biomass, and therefore nitrogen fixation potential. Crops established at the right time, aligned with seasonal rainfall and temperature, have more time to develop biomass and fix nitrogen effectively (Peoples et al., 2009).

Timing of termination

Growing the legume longer can allow it to grow more biomass and fix and accumulate more nitrogen. However, it is not always about the quantity, as quality also matters.

Legume maturity at termination influences residue quality (C:N ratio) and nitrogen release (Reeves et al., 2018). A lower C:N ratio will encourage nitrogen mineralisation and faster decomposition, while a higher C:N ratio will immobilise nitrogen and potentially delay mineralisation.

This trade-off is especially important in cool conditions, where breakdown is slower. In cold seasons, consider earlier termination to allow more time for mineralisation before the cash crop is sown.

Fallow periods after legume termination are risky, without a following crop to take up nitrogen, losses through leaching, volatilisation, or denitrification can occur (Crews and Peoples, 2005). Consider seasonality and weather forecasts, and plan crop sequences to minimise this gap.

As Jim Clarke from Canada advised:

"Farm to the conditions not to a calendar."

Method of termination

Termination methods influence how quickly legume nitrogen becomes plant-available. Options include:

- Incorporation:
  - Full: Rotary hoe
  - Light: Discing
  - Strip tillage: Partial incorporation
- Surface retention:
  - Rolling/crimping
  - Mowing/mulching
  - Herbicide application

Incorporation accelerates decomposition and nitrogen release by increasing residue-soil contact and microbial access. However, without a following crop, this can increase the risk of nitrogen loss. Surface-retained residues decompose more slowly, but may be safer if the subsequent crop is not yet present (Reeves et al., 2018).

Fresh residues left on the surface can also lose nitrogen rapidly unless appropriately managed. As Geert-Jan van der Burgt cautioned:

"Fresh material is important to incorporate,
otherwise it can be lost energy (C, N) if left on the surface."

Consider the effectiveness of different termination methods for each species. Living mulches or intercropped legumes may require mowing to stimulate root sloughing and nitrogen cycling.

Ultimately, termination is a lever, use it to align nitrogen release with the vegetable crop's nutrient demand.

Irrigation

Microbial breakdown of residues and nitrogen mineralisation rely on moisture. In dry soils, the process slows or stops entirely. If water is available, consider irrigating after termination to support residue decomposition and stimulate nitrogen release.

Designing the system for the vegetable crop

Growing a legume well is only part of the story. For nitrogen fixation to benefit the farming system, it must be converted into available nitrogen for the vegetable crop, which is ultimately the economic driver. The goal is to align nitrogen supply from legumes with the crop's nitrogen demand – maximising uptake, minimising losses, and improving input efficiency.

Design rotations to capture nitrogen

The placement of legumes within the rotation has a major impact on nitrogen outcomes. To maximise benefit:

- Follow legumes with nitrogen-hungry crops like corn, potatoes, or brassicas. These crops can capitalise on released nitrogen and reduce the need for synthetic fertiliser.
- Avoid placing legumes back-to-back. Planting a legume cash crop after a legume cover crop can lead to oversupply and inefficient nitrogen use.
- Avoid growing legumes before low nitrogen-demanding crops. Leafy vegetables may not use all the available nitrogen, increasing the risk of losses through leaching or volatilisation.

Timing is critical. Work backward from the planned vegetable crop planting date to determine the window for legume growth and termination. This ensures that the cash crop's requirements (timing, soil preparation, and fertiliser needs) remain the priority.

Key considerations in system design include:

- Weather patterns, for example, hot/wet versus hot/dry conditions
- Seasonality and temperature
- Soil type and drainage
- Operational constraints and available equipment

Consider crop nitrogen uptake

Start with the basics: what does the crop need, and when? Different vegetable crops require nitrogen at different stages and in different amounts. Understanding nutrient uptake curves allows better alignment between nitrogen release from legumes with peak crop demand.

As John Warmerdam from the USA emphasised:

"Focus on nutrition, timing, and the crop's agronomic needs. Do what counts."


Figures 52 & 53: (From L to R) Martin Chaves (2024 USA Nuffield Scholar), grower John Warmerdam and Author standing in plum orchard; plum orchard with carefully spaced and pruned trees to avoid shading of each other (Author, 2024).

The aim is synchrony, avoiding both:

- Excess asynchrony: Nitrogen release exceeds crop need, leading to losses or overstimulation.
- Insufficient asynchrony: Nitrogen is unavailable when the crop needs it most, reducing yield or quality.

To maximise synchrony, apply the 4R principles: right source, right rate, right time, right place.

As Lennart Fuches from the Netherlands noted:

“Think about surplus and deficit. Don’t put extra on just in case,
think about your losses”

Synchronise nitrogen availability with crop demand

To minimise nitrogen loss and maximise use efficiency, consider the following practices (Guinet et al., 2020; Crews and Peoples, 2005):

- Avoid extended fallow periods after legumes.
- Plant the next crop (or a cover crop) shortly after legume termination to capture mineralised nitrogen.
- Delay residue incorporation until closer to planting to retain nitrogen in organic form.
- Grow grass-legume mixes to balance nitrogen release. Grasses (high C:N) slow mineralisation, legumes (low C:N) accelerate it. Together, they can smooth release over time.

Measure to manage

Relying solely on observation can result in under- or over-fertilisation. Use available tools to inform decisions and fine-tune fertiliser programs.

Soil testing

- Test soil at legume termination and before vegetable planting to quantify nitrate and ammonium.
- Use emerging tools like the Hot Water Extractable Organic Nitrogen (HWEON) test to assess potentially mineralisable nitrogen. These results can be paired with local weather data to estimate nitrogen release over the crop's growing period.

Biomass sampling

As outlined earlier in the report, take biomass cuts at termination and send a sub-sample for nitrogen (%) and carbon (%) analysis. Use this data to calculate:

Legume N (kg/ha) = (%N ÷ 100) × biomass (t/ha) × 1000

Incorporate root factors to estimate belowground nitrogen.

Prepare a nitrogen budget

Think of nitrogen like money – what comes in, what's needed, and what's left. Create a nitrogen budget that considers:

- Assets: Soil mineral nitrogen, legume nitrogen, fertiliser nitrogen
- Liabilities: Crop uptake (based on expected growth stages), plus estimated losses (leaching, denitrification, volatilisation)
- Equity: Soil OM as a long-term reserve

This helps determine how much synthetic fertiliser is required.

Table 14: Example nitrogen budget.

	Quantity (kg N/ha)
Nitrogen Assets	
Soil mineral N	
Legume N	
Fertiliser N	
Total nitrogen assets	
Nitrogen liabilities	
Crop uptake (consider needs at different growth stages)	
Losses (denitrification, leaching, volatilisation)	
Total nitrogen liabilities	
Net nitrogen surplus/deficit	
Equity	
Organic matter	

Fertiliser approaches

Many growers begin by reducing base fertiliser by 30–40 kg N/ha where legumes have been used, then fine-tune side-dress rates using in-season monitoring. This gradual approach reduces risk and allows growers to build confidence over time.

Monitor the vegetable crop

Crop monitoring tools help assess whether nitrogen is sufficient, deficient, or excessive:

- Sap tests: Reflect what the plant is actively absorbing; useful for short-term adjustments.
- Tissue tests: Show historical uptake and total stored nutrients; useful for long-term planning.
- Chlorophyll meters: Non-destructive tools that measure greenness (chlorophyll), which is closely linked to nitrogen status. Requires calibration with known reference strips.

These tools provide real-time feedback to refine nitrogen decisions and reduce unnecessary inputs.

Figures 54 & 55: (From L to R) James Alexander, UK, holding N-tester meter from Yara used to measure nitrogen in cereal crops; box of device (Author, 2024).

Modelling to inform decision making

Australia currently lacks decision-support models to predict nitrogen mineralisation from legume residues. However, international tools offer inspiration:

- Sustainable Vegetable Systems tool (New Zealand): Uses HWEON results and climate data to predict in-field nitrogen release.
- MERCI tool (France): Combines cover crop biomass and weather data to model mineralisation (Constantin et al., 2024).

While these tools require calibration to local soils and crops, they highlight the potential for future development in the Australian context.

Systems thinking and reflections

While the focus of this report is on legume management and nitrogen dynamics, my Nuffield travels revealed broader insights that underpin not just the use of legumes but also the foundations of resilient, efficient, and sustainable farming systems. Two themes stood out consistently: the importance of people, and the central role of healthy soils.

People drive success: mindset, learning and collaboration

Across farms, research centres, and organisations, one message was clear: success starts with people. Whether it's adopting legumes, refining rotations, or redesigning systems, the most effective outcomes came from growers with a mindset of continuous learning, trial and error, and collaborative exchange.

"Don't give up on the first attempt of things."
Toby Baxter, UK

"Are you going to make it work, or are you just going to try it?"
Laura Van Eerd, Canada

The most resilient systems were not developed in isolation. They thrived in networks where growers worked with researchers, shared observations with peers, and transferred learnings between organic and conventional systems. Initiatives like *Ver de Terre* in France created an interactive map of grower profiles, and the Yield Enhancement Network in Canada exemplify this culture of shared learning and innovation.

Another recurring theme was the importance of language and framing. As one grower explained:

"Change needs to be worthwhile enough to try, because it can be risky."

This highlights the need to communicate new practices in simple, specific, and context-relevant ways, especially when dealing with the complexities of biological systems. Matching communication tools to different learning styles is crucial for building trust and uptake.

Healthy farming systems build the foundation for nitrogen cycling

Beyond the role of legumes, the growers I visited consistently pointed to soil health as the bedrock of productive and resilient systems. Their practices, including reduced tillage, species diversity, composting, and cover cropping, were all designed to support the soil as a living ecosystem.

There was a shared shift away from rigid, prescriptive "recipe farming" toward more responsive, biological thinking:

"Get away from recipe thinking."
Janjo de Haan, Netherlands

"Farm to the conditions, not to a calendar."
Jim Clarke, Canada

"What you do depends on the conditions of your soil."
Lennart Fuches, Netherlands

"The microorganisms are playing their own game
– some things will happen and you won't know why."
Marie Morineau, France

This mindset recognised that soils are not just a medium but a dynamic system, deserving of observation and care. Several growers described their soil as a living partner in the farming enterprise – something to feed, protect and learn from.

"Soil is a living thing that needs to eat. Get close to nature and its origins."
Francois Mulet, France

"You can produce food even with nature.
It will help manage weeds, pests and disease."
Marie Morineau, France



Figures 56 to 58: (From L to R) Soil from Marie Morineau farm in France; Blake Vince (Nuffield Canada Chair) and Author inspecting cover crop and soil; Erwin Westers soil in Netherlands (Author, 2024).

There was also a clear understanding that rebuilding soil fertility is a long game:

"Building soil fertility over 20 years gets you 95% of the way there.
The remaining 5% is topped up with inputs."
Geert-Jan van der Burgt, Netherlands

"Start with the basics of soil health, like cover cropping and reduced tillage, before jumping straight into applying biologicals."
Lauren Benoit, Canada

This patient, cumulative approach often yielded quieter but more resilient systems – less dependent on external inputs, more consistent in performance, and more forgiving under stress.

"If you get the soil right, everything will look after itself."
James Alexander, UK

"Mistakes are okay, but it's about logic and thinking before doing."
Marie Morineau, France

For many, this was not just agronomy. It was a set of values, a decision to farm with complexity, rather than trying to control it. It's this mindset, rooted in experimentation, reflection, and long-term thinking, that underpins successful use of legumes, and more broadly, regenerative farming practice.

Figures 59 & 60: Jan Willem Bakker's soil in Netherlands under reduced tillage (left) vs conventional tillage (right), (Author, 2024).

Conclusions

Legumes hold real promise as a biological source of nitrogen, offering vegetable growers an opportunity to reshape their nitrogen management. They contribute to reducing reliance on synthetic inputs, improving soil fertility and function, and building system resilience.

Their effective use involves more than just slotting them into the rotation. It requires an understanding of biology, context, and system dynamics, paired with a mindset of observation, experimentation, and adaptation.

A key insight from this journey is that there is no simple formula for matching nitrogen availability from legumes with the nitrogen needs of vegetable crops. The process is biologically driven, shaped by season, soil type, and management practices. Research shows that typically only 30–40% of the nitrogen fixed by a legume is recovered by the next crop. The rest is either mineralised slowly, lost to the environment, or incorporated into soil OM.

Across case studies and farm visits, several consistent principles emerged:

- **Grow the legume crop well**. The basics matter - choose the right species, inoculate with rhizobia, manage pH, and build good biomass.
- **Context is everything**. Legume placement in a rotation must match crop demand and opportunity – whether rebuilding after a nutrient-hungry crop or supplying one ahead.
- **Weather and management drive mineralisation**. Warm, moist soils speed up nitrogen release. Termination timing and method matter - high C:N ratios or retained surface residues can slow mineralisation.
- **Nitrogen losses still happen**. Like synthetic nitrogen, legume-derived nitrogen can leach, volatilise or denitrify if not captured. Fallow periods after legumes can increase risk of losses.
- **Each vegetable crop is different**. Effective synchrony requires an understanding of crop-specific nutrient timing and uptake.
- **Tools help, but trial and error is most powerful**. Tools like biomass sampling, soil and crop tissue tests help, but progress comes through observation, learning and adaptation.

What stood out most were the farmers themselves – their mindset, curiosity, and willingness to adapt. Those who had successfully integrated legumes had made deliberate shifts in thinking. They observed their soils closely, invested in learning, and were open to change. Their motivation was often deeper than cost or yield; it was about farming with more independence, more integrity, and more alignment with nature.

Most were not measuring every kilogram of nitrogen, instead drew on intuition, observation, and understanding of principles. They did not aim to control every variable, but to work with complexity, not against it.

One unprompted theme that emerged again and again was the importance of soil health. While legumes were a valuable tool, they were rarely used in isolation. They formed part of a broader philosophy: to rebuild soils through cover cropping, reduced tillage, and increased diversity. Soil health was woven through every decision.

This scholarship has changed the way I think, not just about legumes, but about farming systems and problem-solving more broadly. It reminded me that progress does not come from perfection. It comes from getting started, staying consistent, and making small, thoughtful adjustments over time.

It also reinforced the power of combining science with practice. Science helps explain the mechanisms; growers bring them to life through testing, adaptation, and pushing boundaries in the real world.

Recommendations

Legumes offer a real opportunity to improve nitrogen management in vegetable systems, but their success relies on practical knowledge, adaptive management, and system-wide thinking. The following recommendations are directed at growers, advisors, researchers, and the broader industry.

For researchers

- Focus on applied, systems-based trials that explore how legumes perform in real-world rotations and under different management approaches.
- Develop simple decision-support tools (e.g. nitrogen budgeting templates, residue calculators, visual guides) adapted to Australian soils, crops, and climates.
- Measure beyond nitrogen, capturing the broader system benefits of legumes such as improved soil structure, microbial activity, and resilience.
- Explore native legume potential, supporting evaluation and potential commercialisation of locally adapted species.

For growers

- Start small and build confidence – trial legumes in strips or paddocks, particularly before nitrogen-hungry crops like brassicas or corn.
- Focus on the basics – choose suitable species, inoculate with the right rhizobia, grow strong biomass, and manage termination timing.
- Use simple tools like biomass cuts, sap tests, and nitrogen budgets to inform fertiliser decisions.
- Expect variability – start by reducing fertiliser modestly and adjust over time with monitoring.

For advisors

- Tailor legume strategies to system constraints – climate, crop rotation, labour, and machinery matter as much as species choice.
- Promote learning – support growers to observe, trial, and refine, rather than aiming for perfection from the start.
- Communicate simply and practically – reframe complexity into actionable steps using tools, visuals, and field-based insights.

For industry

- Invest in on-farm demonstration and peer learning, particularly networks that connect organic and conventional growers.
- Improve access to legume seed, especially diverse and native options.
- Recognise long-term soil-building practices through sustainability incentives, policy support, or industry metrics that go beyond yield.

Legumes are not a universal solution, but they are a valuable tool. With thoughtful management and system thinking, they can reduce inputs, support soil health, and enhance resilience in vegetable production. The next step is to test, observe, and adapt together.

References

AUSVEG (2024) *Vegetable Industry Sentiment Report*,.

Baluska, F. and Vivanco, J. (2012) *Secretions and Exudates in Biological Systems*, [Online]. Available at http://www.springer.com/series/8094.

Van Der Burgt, G. J., Timmermans, B. and Havenga De Poel, H. (2021) *Evaluation Planty Organic 2012-2020 Plant-based fertilizer: nitrogen and organic matter*, [Online]. Available at www.spna.nl.

Constantin, J., Minette, S., Vericel, G., Jordan-Meille, L. and Justes, E. (2024) ‘MERCI: a simple method and decision-support tool to estimate availability of nitrogen from a wide range of cover crops to the next cash crop’, *Plant and Soil*, Springer Science and Business Media Deutschland GmbH, vol. 494, no. 1–2, pp. 333–351 [Online]. DOI: 10.1007/s11104-023-06283-1.

Crews, T. E. and Peoples, M. B. (2005) ‘Can the synchrony of nitrogen supply and crop demand be improved in legume and fertilizer-based agroecosystems? A review’, *Nutrient Cycling in Agroecosystems*, vol. 72, no. 2 [Online]. DOI: 10.1007/s10705-004-6480-1.

Farquharson, C. E., Elizabeth Farquharson, A. A., Ballard, R. A., Herridge, D. F., Ryder, M. H., Denton, M. D., Webster, A., Yates, R. J., Seymour, N. P., Deaker, R. J., Hartley, E. J., Gemell, G., Hackney, B., O, G. W., Seymour, N. and Yates, R. (2022) *Inoculating Legumes: Practice and Science*,.

Fox, R. H., Myers, R. J. K. and Vallis, I. (1990) *The nitrogen mineralization rate of legume residues in soil as influenced by their polyphenol, lignin, and nitrogen contents*, *Plant and Soil*, vol. 129.

Fresh Logic (2024) *All Vegetables-Overview*,.

Gonzales-Lopez, J. and Gonzales-Martinez, A. (2021) *Nitrogen Cycle : Ecology, Biotechnological Applications and Environmental Impacts*, Gonzales-Lopez, J. and Gonzales-Martinez, A. (eds), 1st edn, Granada, Spain, CRC Press, vol. 1 [Online]. Available at https://www.taylorfrancis.com/books/edit/10.1201/9780429291180/nitrogen-cycle-jesus-gonzalez-lopez-alejandro-gonzalez-martinez (Accessed 17 June 2025).

Grigg, J., Ogilvie, C. and Van Eerd, L. (2021) *Wheat Going to Corn: Underseed Red Clover*, [Online]. Available at http://mccc.msu.edu/selector-tool/-.

Grzyb, A., Wolna-Maruwka, A. and Niewiadomska, A. (2020) ‘Environmental factors affecting the mineralization of crop residues’, *Agronomy*, MDPI AG, vol. 10, no. 12 [Online]. DOI: 10.3390/agronomy10121951.

Guinet, M., Nicolardot, B. and Voisin, A. S. (2020) ‘Nitrogen benefits of ten legume pre-crops for wheat assessed by field measurements and modelling’, *European Journal of Agronomy*, Elsevier B.V., vol. 120 [Online]. DOI: 10.1016/j.eja.2020.126151.

Huber, D., Römheld, V. and Weinmann, M. (2011) ‘Relationship between Nutrition, Plant Diseases and Pests’, in *Marschner’s Mineral Nutrition of Higher Plants: Third Edition*, Elsevier Inc., pp. 283–298 [Online]. DOI: 10.1016/B978-0-12-384905-2.00010-8.

Johnson, C., Albrech, G., Ketterings, Q., Beckman, J. and Stockin, K. (2005) *Nitrogen Basics-The Nitrogen Cycle Agronomy Fact Sheet Series*, [Online]. Available at http://nmsp.css.cornell.edu.

Kebede, E. (2021) ‘Contribution, Utilization, and Improvement of Legumes-Driven Biological Nitrogen Fixation in Agricultural Systems’, *Frontiers in Sustainable Food Systems*, Frontiers Media S.A., vol. 5 [Online]. DOI: 10.3389/fsufs.2021.767998.

Li, F., Sørensen, P., Li, X. and Olesen, J. E. (2020) ‘Carbon and nitrogen mineralization differ between incorporated shoots and roots of legume versus non-legume based cover crops’, *Plant and Soil*, Springer, vol. 446, no. 1–2, pp. 243–257 [Online]. DOI: 10.1007/s11104-019-04358-6.

Liebman, A. M., Grossman, J., Brown, M., Wells, M. S., Reberg-Horton, S. C. and Shi, W. (2018) ‘Legume cover crops and tillage impact nitrogen dynamics in organic corn production’, *Agronomy Journal*, American Society of Agronomy, vol. 110, no. 3, pp. 1046–1057 [Online]. DOI: 10.2134/agronj2017.08.0474.

Lupwayi, N. Z. and Soon, Y. K. (2015) ‘Carbon and Nitrogen Release from Legume Crop Residues for Three Subsequent Crops’, *Soil Science Society of America Journal*, Wiley, vol. 79, no. 6, pp. 1650–1659 [Online]. DOI: 10.2136/sssaj2015.05.0198.

Maraseni, T. N., Cockfield, G., Maroulis, J. and Chen, G. (2010) ‘An assessment of greenhouse gas emissions from the Australian vegetables industry.’, *Journal of environmental science and health. Part. B, Pesticides, food contaminants, and agricultural wastes*, vol. 45, no. 6, pp. 578–588 [Online]. DOI: 10.1080/03601234.2010.493497.

Masclaux-Daubresse, C., Daniel-Vedele, F., Dechorgnat, J., Chardon, F., Gaufichon, L. and Suzuki, A. (2010) ‘Nitrogen uptake, assimilation and remobilization in plants: Challenges for sustainable and productive agriculture’, *Annals of Botany*, vol. 105, no. 7 [Online]. DOI: 10.1093/aob/mcq028.

Meena, V. S., Mishra, P. K., Bisht, J. K. and Pattanayak, A. (2017) *Agriculturally important microbes for sustainable agriculture*, *Agriculturally Important Microbes for Sustainable Agriculture*, Springer Singapore, vol. 2 [Online]. DOI: 10.1007/978-981-10-5343-6.

Menegat, S., Ledo, A. and Tirado, R. (2022) ‘Greenhouse gas emissions from global production and use of nitrogen synthetic fertilisers in agriculture’, *Scientific Reports*, Nature Research, vol. 12, no. 1 [Online]. DOI: 10.1038/s41598-022-18773-w.

Newton, W. E. (2007) ‘Physiology, Biochemistry, and Molecular Biology of Nitrogen Fixation’, in Bothe, H., Ferguson, S., and Newton, W. (eds), *Biology of the Nitrogen Cycle*.

Oliveira, M., Rebac, D., Coutinho, J., Ferreira, L. and Trindade, H. (2020) ‘Nitrogen mineralization of legume residues: Interactions between species, temperature and placement in soil’, *Spanish Journal of Agricultural Research*, Ministerio de Agricultura Pesca y Alimentacion, vol. 18, no. 1 [Online]. DOI: 10.5424/sjar/2020181-15174.

Palm, C. A. and Saschez, P. A. (1990) *Nitrogen release from the leaves of some tropical legumes as affected by their lignin and polyphenolic contents*, *Sal Eiol. Bwchcm*, vol. 23.

Peoples, M. B., Brockwell, J., Hunt, J. R., Swan, A. D., Watson, L., Hayes, R. C., Li, G. D., Hackney, B., Nuttall, J. G., Davies, S. L. and Fillery, I. R. P. (2012) 'Factors affecting the potential contributions of N2 fixation by legumes in Australian pasture systems', *Crop and Pasture Science*, vol. 63, no. 9, pp. 759–786 [Online]. DOI: 10.1071/CP12123.

Peoples, M. B., Hauggaard-Nielsen, H., Huguenin-Elie, O., Jensen, E. S., Justes, E. and Williams, M. (2018) 'The contributions of legumes to reducing the environmental risk of agricultural production', in *Agroecosystem Diversity: Reconciling Contemporary Agriculture and Environmental Quality*, Elsevier, pp. 123–143 [Online]. DOI: 10.1016/B978-0-12-811050-8.00008-X.

Peoples, M, Brockwell, J., Herridge, D., Rochester, I., Alves, B., Urquiaga, S., Boddey, R., Dakora, F., Bhattarai, S., Maskey, S., Sampet, C., Rerkasem, B., Khan, D., Hauggaard-Nielsen, H. and Jensen, E. (2009) 'The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems', *SYMBIOSIS*, vol. 48, pp. 1–17.

Peoples, MB, Herridge, D., Alves, R., Urquiaga, S., Boddey, R., Dakora, F., Bhattarai, S., Maskey, S., Sampet, C., Rerkasem, B., Khans, D., Hauggaard-Nielsen, H. and Jensen, B. (2009) 'The contributions of nitrogen-fixing crop legumes to the productivity of agricultural systems', vol. 48, pp. 1–17.

Pietikainen, J., Pettersson, M. and Baath, E. (2005) 'Comparison of temperature effects on soil respiration and bacterial and fungal growth rates', *FEMS Microbiology Ecology*, Elsevier, vol. 52, no. 1, pp. 49–58.

Planfarm (2024) *National Vegetable and Onion Benchmarks - 2023 Season*,.

Plett, D. C., Ranathunge, K., Melino, V. J., Kuya, N., Uga, Y. and Kronzucker, H. J. (2020) 'The intersection of nitrogen nutrition and water use in plants: New paths toward improved crop productivity', *Journal of Experimental Botany*, Oxford University Press, vol. 71, no. 15 [Online]. DOI: 10.1093/jxb/eraa049.

Reeves, S., Wang, W., Heenan, M., Halpin, N., Mcshane, T., Rickert, A. and Royle, A. (2018) *Nitrogen mineralisation of legume residues*, *Proc Aust Soc Sugar Cane Technol*, vol. 40.

Schwenke, G. (2022) *Nitrogen loss pathways - how much do we lose and in what form under different situations?*, [Online]. Available at https://grdc.com.au/resources-and-publications/grdc-update-papers/tab-content/grdc-update-papers/2022/06/nitrogen-loss-pathways-how-much-do-we-lose-and-in-what-form-under-different-situations (Accessed 25 July 2025).

Sondag, D. A., Gaudin, A. C. M., Mitchell, J. P. and Pittelkow, C. M. (2025) 'Priming the decomposition of cover crop residues in no-till organic cropping systems', *Agriculture, Ecosystems and Environment*, Elsevier B.V., vol. 388 [Online]. DOI: 10.1016/j.agee.2025.109651.

Stacey, G. (2007) 'The Rhizobium-Legume nitrogen-fixing symbiosis', in Bothe, H., Ferguson, S., and Newton, W. (eds), *Biology of the Nitrogen Cycle*.

Stagnari, F., Maggio, A., Galieni, A. and Pisante, M. (2017) 'Multiple benefits of legumes for agriculture sustainability: an overview', *Chemical and Biological Technologies in Agriculture*, Springer International Publishing, vol. 4, no. 1 [Online]. DOI: 10.1186/s40538-016-0085-1.

Swan, T., Dunn, M., Kirkegaard, J., Peoples, M., Goward, L., Leighton, E., Sandral, G., Hunt, J., Bullock, M., Pumpa, R., Fiske, K., Woodford-Smith, A., Reardon, D., Barry, M. and Burns, H. (2022) *What is the N legacy following pulses for subsequent crops and what management options are important to optimise N fixation?*,.

Tegeder, M. and Masclaux-Daubresse, C. (2018) ‘Source and sink mechanisms of nitrogen transport and use’, *New Phytologist*, vol. 217, no. 1 [Online]. DOI: 10.1111/nph.14876.

Uchida, R. and Silva, J. (2000) ‘Essential Nutrients for Plant Growth: Nutrient Functions & Deficiency Symptoms’, in *Plant Nutrient Management in Hawaii’s Soils*, Manoa, Hawaii.

USDA (2011) *Carbon to Nitrogen Ratios in Cropping Systems*, [Online]. Available at http://www.nm.nrcs.usda.gov/Technical/tech-notes/agro/.

Veromann, E., Toome, M., Kännaste, A., Kaasik, R., Copolovici, L., Flink, J., Kovács, G., Narits, L., Luik, A. and Niinemets, Ü. (2013) ‘Effects of nitrogen fertilization on insect pests, their parasitoids, plant diseases and volatile organic compounds in Brassica napus’, *Crop Protection*, vol. 43, pp. 79–88 [Online]. DOI: 10.1016/j.cropro.2012.09.001.

Virk, A. L., Lin, B. J., Kan, Z. R., Qi, J. Y., Dang, Y. P., Lal, R., Zhao, X. and Zhang, H. L. (2022) ‘Simultaneous effects of legume cultivation on carbon and nitrogen accumulation in soil’, in *Advances in Agronomy*, Academic Press Inc., vol. 171, pp. 75–110 [Online]. DOI: 10.1016/bs.agron.2021.08.002.

White, P. J., George, T. S., Gregory, P. J., Bengough, A. G., Hallett, P. D. and McKenzie, B. M. (2013) ‘Matching roots to their environment’, *Annals of Botany*, vol. 112, no. 2, pp. 207–222 [Online]. DOI: 10.1093/aob/mct123.