Vineyard Floor Management: A Sustainability Nexus with a Focus on Undervine Weeding

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Dr Charles N Merfield. MRSNZ

The BHU Future Farming Centre

Permanent Agriculture and Horticulture Science and Extension

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1. Introduction

This report was instigated in 2014 by Organic Winegrowers NZ[1] requesting a booklet on organic undervine weed control, which has been published as Lambourne & Merfield (2017). However, it quickly became clear as I was writing the weeding booklet that it is impossible to separate out undervine weed management from the management of the whole vineyard floor. It also struck me that many of the sustainability issues facing viticulture, and, indeed all perennial crops, e.g., pipfruit, stone fruit, nuts, vines, bush / cane fruit, come together in a nexus around management of the vineyard / orchard floor as all the issues are all interlinked / intertwined and meet on the vineyard floor. The key sustainability issues that are linked together on the floor are:

- Replacing herbicide strips / bare undervine soil for weed management / crop competition with a living mulch of growing plants;
- Nitrogen supply and management via legumes, to replace synthetic nitrogen fertilisers;
- Improving soil health and protecting it from loss (e.g., wind and water erosion);
- Sequestering atmospheric carbon;
- Increasing biodiversity; and
- Conservation biocontrol of vineyard pests & diseases.

While this report was originally written for New Zealand organic winegrowers, the general message, as well as many of the specific details, are as applicable to all other perennial cropping systems, organic and non-organic, anywhere in the world. It is therefore hoped that the report will stimulate discussion, provide useful insights and some practical solutions for the growers of all perennial crops globally.

As noted above the undervine weed control booklet was published in 2017, but, this wider report on the sustainability nexus has not been formally published, though a number of copies of the final draft are in circulation. Corrections and edits have been made to that final draft version to create this, the full and final version of the report.

The report still contains the original material for the undervine weed control booklet (Lambourne & Merfield, 2017), but put in the wider context of the vineyard floor. The section on undervine weeding is therefore considerably larger and more detailed than it would be had the report started with a focus on the wider issue of sustainable vineyard floor management, but, I have left it in as I consider the information is of value and not all of it was used in Lambourne & Merfield. The thermal weeding section is particularly detailed as thermal weeding is one of my particular interests.

Charles Merfield October 2019.

[1] www.organicwinenz.com

2. Summary

- This report started as a practical guide on non-chemical weed management in organic vineyards in New Zealand. However, during writing, it became clear that, undervine weed management could not be sensibly separated from the management of the rest of the vineyard floor, so the report was expanded to look at these wider issues.
- While written for organic winegrowing in New Zealand, the report is equally appliable to both organic and non-organic systems, and any perennial crop production system, e.g., pipfruit, stone fruit, nuts, vines, bush / cane fruit, not just grape vines, in any country, not just New Zealand.
- The vineyard / orchard floor is considered to be a nexus where a number of issues meet, including:
  - Replacing herbicide strips / bare undervine soil for weed management / crop competition with a living mulch of growing plants;
  - Nitrogen supply and management via legumes, to replace synthetic nitrogen fertilisers;
  - Improving soil health and protecting it from loss (e.g., wind and water erosion);
  - Sequestering atmospheric carbon;
  - Increasing biodiversity; and
  - Conservation biocontrol of vineyard pests & diseases.
- All of these have an impact on the multiple, massive global challenges that humanity faces, such as climate change / global heating, biodiversity loss / the 6th great extinction, loss of soil, excess P and N in waterways, etc.
- Many of the agronomic technologies, the above solutions are aiming to supplant or reduce, e.g., nitrogen fertilisers, herbicides, and insecticides, are often part of the cause of the global challenges, and therefore, the solutions are not considered voluntary, but, are essential if perennial crop systems are to make their contribution to solving the global challenges.
- The report analysis and provides the theoretical background to the key vineyard floor systems:
  - The soil system, how it functions and why soil health is critical;
  - The nitrogen cycle and why its understanding is critical for N management;
  - The vine (perennial plant) system and how it interacts with soil and other plants;
  - Redefining weeds from any 'non-crop plant' to plants causing 'real and actual harm'.
- The report then provides practical solutions and alternative ways of managing the vineyard floor
  - The use of beneficial plants in both the undervine and mid-row to:
    - Out compete weeds and therefore replace the herbicide strip with a mulch of living plants;
    - Supply nitrogen for the crop (vines);
    - Provide conservation biological control;
    - Protect the soil (especially undervine), and enhance soil health;
    - Sequester atmospheric carbon;
    - Increase biodiversity, both above and below ground.
- The report then provides details on various non-chemical undervine weeding techniques including:
  - Mowing;
  - Cultivation / tillage
  - Thermal;
  - Electrothermal;
  - Certified organic herbicides.
- A range of further information sources are provided.

3. Sustainable vineyard floor management

Organic wine production in New Zealand is expanding rapidly and non-organic wine producers are also increasingly cognisant of the need to improve their vineyard's environmental sustainability. While synthetic agrichemicals and fertilisers have been prohibited in organics for decades, in non-organic production sizeable advances have been made in the reduction of foliar pesticides and fungicides, with the use of biological control and more environmentally benign chemistry. However, the undervine has not seen an equivalent improvement. In organic viticulture the main options are mowing or cultivation while in non-organic production, herbicided undervine are still the dominant practice. There is therefore increasing interest among both organic and non-organic viticulturalists to improve the sustainability of undervine, and vineyard floor management as a whole.

This booklet aims to give both organic and non-organic winegrowers an introduction and overview of sustainable / non-chemical vineyard floor management. It is aimed at growers of all levels of experience, from those who are new to winegrowing to those who have been in the industry their whole life.

3.1. Reappraising 'just how things are done'

Within non-organic viticulture, the use of herbicides to maintain a vegetation free undervine has become almost universal since herbicides became widely available in the 1950s. This practice is not restricted to viticulture, with nearly every perennial tree, vine, and bush production system adopting the practice, even extending it to a completely vegetation free soil surface. The reason for the dominance of this approach is that plants compete with each other for light, soil nutrients, and water. Eliminating under crop vegetation can therefore reduce competition with the crop with potential increases in yield, and other benefits such as reduced water and nutrient requirements.

Such was the initial success of removing vegetation from the undervine, that after generations of use, the practice became simply 'just how things are done' and it became inconceivable that things could be done another way, or that there was even another way of doing it in the past. And, to some extent, organic agriculture followed the same trend of eliminating undervine vegetation, except using non-chemical techniques, such as tillage / cultivation. However, like many initially successful novel practices, upon becoming dominant, an increasing number of problems became apparent, such as soil compaction, degraded soil biology, loss of soil organic matter / carbon, physical loss of soil, diminished biodiversity, excess N, P and sediment in waterways, simplified vineyard ecosystems leading to pest and disease build-ups and herbicide resistant weeds, for example.

In light of evolving industry aims, such as increasing the amount of organic and biodynamic viticulture and improving the sustainability of all winegrowing, it is considered timely to reappraise the 'just how things are done' of undervine and vineyard floor management, to re-evaluate practices and re-examine the agronomy to find better and more sustainable practices and make them the new 'just how things are done'.

3.2. The vineyard floor: a nexus for the sustainable future of viticulture

With the significant sustainability improvements in vineyard canopy management, particularly reduced agrichemical use and the introduction of integrated pest & disease management, the vineyard floor is considered the final frontier for sustainable viticulture. The vineyard floor is also a critical nexus: it is where vine management meets and interacts with, soil management, pest & disease management and biodiversity. For example, replacing a bare earth undervine with cover-crops or green manures will increase soil health, biodiversity and can have positive impacts on vines.

The under-vine and the mid-row can also be used for 'conservation biological control'[2] where plants that enhance pests' natural enemies so they control the pests without the need for pesticides, while at the same time improving biodiversity, and soil quality. Biological mulches, e.g., produced from the interrow can assist with disease control by speeding up decomposition of vine prunings and creating a physical barrier to spore transmission, while improving undervine soil biology and nutrients.

New and improved vineyard floor management techniques can therefore achieve multiple dividends, and, as many of the outcomes of improved vineyard floor management are critical to the future agronomic and environmental sustainability of New Zealand winegrowing. Not only is the vineyard floor a nexus, it is also considered critical for the industries future.

3.3. A weed by any other name

The advent of the herbicide era around the 1950s and the dramatic simplification and ease of weed control that they permitted, resulted in an equally dramatic shift in farmer, grower and societal perceptions of weeds. Quite simply, plants that had previously been of no concern, were redefined as weeds simply because it was now possible to easily kill them, for example clover seed was considered mandatory in lawn seed mixtures prior to the 1940s and their quality was judged on the percentage of clover (Carleton, 1957), but the advent of selective herbicides that could kill dicots among grasses, rapidly caused the elimination of clover from lawn seed mixtures and from lawns, which was previously impossible at a practical level.

Agriculture and society are now starting another paradigm shift in attitude to weeds. The concept that any given plant species is, and will always be a weed, is evolving. The emerging view is that there are three 'classes' of plants in agri / horticultural systems:

- Crop;
- Non-crop plants;
- Weeds.

Weeds, as a class of plants are therefore shifting from a definition of 'everything else than the crop' to a definition where they must be creating 'real and actual harm' in any given situation to be deemed a weed. The real and actual harm therefore, has to be clearly defined, for example in agri / horticulture, causing economic loss, a physical hazard, poisoning stock, and in the conservation estate invasive weeds, e.g. wilding pines.

It is only under the emerging paradigm, rather than the old 'once a weed, always a weed' perspective that plants can be a weed in one situation but a valuable resource in another. A good example of this is soursob / Bermuda buttercup (*Oxalis pes-caprae*) which in Australian pastoral systems is clearly a weed as it is toxic to stock and out-competes pasture, while in vineyards, it can make for an excellent undervine living mulch as it smothers out other plants, and, as it is winter active so dies back and becomes dormant in spring, it does not compete with vines during their active growth period. The key part of the new weed paradigm is therefore that non-crop plants, i.e., plants that are not weeds, do not need to be eliminated. Indeed even plants that are weeds, only need to be managed to the point that they no longer cause real and actual harm, rather than always being exterminated.

It must be noted that due to the biology of weeds, particularly the longevity of the weed seed bank in the soil, and the prolific reproductive abilities of annual weeds, a long-term perspective has to be taken, as a few unproblematic non-crop plants, can, in just two to three years, become so numerous, that just by shear numbers they do cause real harm. But, within this caveat, weeds only need to be managed and controlled to the point of eliminating harm, not eliminating the all the weed plants all of the time.

[2] en.wikipedia.org/wiki/Biological_pest_control#Conservation

3.4. Aesthetics - the right 'look'

A less commonly discussed aspect of the traditional herbicided undervine, is how it has become accepted as the 'right' way for a vineyard to look. This is not restricted to viticulture, many other agri / horticultural sectors also have broadly accepted views on things such as herbicide strips under fencelines and along roadway edges. Often under organic and non-chemical weed management, it is neither practical or desirable to achieve the same 'manicured' look to a vineyard. This somewhat more 'rugged' look can cause consternation both for vineyard managers and also fellow winegrowers viewing the vineyard.

However, vineyard aesthetics are clearly a matter of taste. What is tasteful now, however, has not always been that way: going back in time, the current bare earth and mown mid-row would of been considered rather sterile, compared to what had gone before. What is now increasingly clear is that aesthetics needs to take a backseat to sustainability issues such as soil protection and biodiversity, such the achieving the traditional manicured vineyard look, ought to become an increasing sign of a badly, not a well managed, vineyard. So, for example, having a few weeds around vines and posts and a longer mid-row sward, as long as it is not negatively effecting production, should not be considered a sign of failure, rather a sign of success.

3.5. The biodiversity value of weeds and non-crop plants

Biodiversity loss is now rated as among the most important global issues (Anon., 2015). Within agriculture and horticulture weeds and non-crop plants represent a significant source of biodiversity in what would otherwise be monocultural systems. This is therefore another key reason to move as many plant species as possible from being classed as weeds (i.e., plants causing real and actual harm) to the non-crop plants category (not causing real and actual harm) to maximise naturally occurring (and therefore cheap) vineyard biodiversity.

3.6. Your mileage will vary - why understanding mechanisms is critical

One of the key effects of pesticides and herbicides was to considerably simplify agri / horticultural systems, almost to the point of it becoming painting by numbers: pest and weed management has been reduced to simply identifying the pest or weed species, looking up what agri-chemical will control it in the production system in question and then applying the spray as per instructions. The flip-side of this, is non-chemical techniques are often considerably more complex: rarely are there recipes / painting by numbers solutions for production problems, rather the farmer or grower has to understand the production system in some detail to be able to identify potential solutions. And, many solutions are highly site specific: what works at one vineyard, may fail in another. For example, in a vineyard with low vigour clover may give a useful boost of nitrogen, while in an over-vigorous vineyard, more N from clover will only make matters worse. Therefore understanding what is going on 'under the hood' of vineyard systems is therefore critical. That is the purpose of the next section of this handbook.

4. Vineyard floor system components - the theory

The vineyard system has a five key biological components:

- The soil;
- The vines;
- The non-vine plant flora (both weeds and non-crop plants);
- Vine pests & diseases;
- Biological control organisms.

These systems all interact, e.g., non-crop plants can both help increase and decrease pests and disease levels, so it is critical to understand how each system functions by itself and then how they interact.

4.1. The soil system

The value of a healthy compared with an unhealthy soil is impossible to overstate. Soil health is clearly critical for healthy plant growth - plants will die in a sufficiently unhealthy soil. In addition many soil functions are integral to many environmental problems such as nutrient pollution of streams and rivers, biodiversity loss and climate change. The need to improve soil health is therefore an increasingly critical component of good viticulture and all of agri / horticulture.

4.1.1. Maintaining a healthy well functioning soil

Soil is the most physically and chemically complex 'substance' on the planet and it is also the most complex ecosystem, with the belowground biomass and biodiversity typically being an order of magnitude greater than the aboveground system. This booklet can therefore only touch very lightly on the relevant key points, and readers are encouraged to gain deeper understanding from the many excellent soil textbooks available, some of which are listed in further reading.

The key understanding of the soil system is that it is a living and dynamic system, akin to an animal, e.g., a cow. The soil system needs a continual input of nutrients and energy (i.e., food) to function effectively and to be healthy just the same as an animal. The primary source of soil food is freshly dead plant remains, as plants are the primary producers in all food chains / webs, as only plants capture the energy in sunlight. Plant remains, such as leaves and roots, are either directly consumed by soil organisms or after passing through above-ground herbivores, such as livestock, and being returned to the soil as dung. The transfer of the nutrients and energy in the plant matter, through the soil food web creates a healthy soil, the key elements for viticulture are:

- Good soil organic matter levels;
- Good physical structure;
- Un-compacted;
- Good water holding capacity;
- Effective drainage;
- Aerobic (not anaerobic);
- Resistant to erosion
- Good nutrient holding capacity (anion and cation exchange capacity);
- pH buffering
- Good levels of available plant nutrients.

The key point is if there is a lack of regular plant residues or equivalent material, e.g., manure or compost, entering the soil, because the soil is bare due to herbicide or cultivation, then the above positive benefits will be lost and their negative counterparts, e.g., poor structure, compaction, poor drainage, eroding, etc., will come to the fore. Creating a healthy soil is therefore not a destination, but a continual endeavour.

4.1.2. Compaction and cultivation

After ensuring that there is a regular input of plant residues or other organic matter into the soil system, the next two major management impacts on soil in vineyards are compaction and cultivation.

The main source of compaction in vineyards are tractors. Due to the nature of the trellis production system, tractor wheelings are confined to a single tramline (unlike cropping) which has the positive effect of eliminating compaction from the rest of the vineyard floor, but the negative effect of maximising the compaction in the tramlines. These compacted tramlines can be sufficiently dense that they form an impenetrable barrier to vine roots to a depth of a meter or more, thus preventing or restricting vines accessing the soil in the mid-row. In addition, all of the above elements of a healthy soil are markedly reduced by compaction.

Compaction also occurs in the undervine area where herbicides are used to eliminate weeds. This is because soil needs actively growing plants to maintain its functionality, so without a cover of plants, soil functions, including the formation of soil structure, and thus compaction prevention, cause the soil to slump and compact, sometimes to densities close to that in tractor wheelings.

Cultivation is almost always harmful to soil health, especially with long-term use. However, judicious use of cultivation may be required to address other issues, the key one being compaction. A nuanced view of cultivation is therefore required: frequent cultivation of the undervine to kill weeds, especially with powered tools, can have an even bigger impact on soil quality than herbicides; but infrequent, targeted cultivation using draft tools, may result in an overall improvement in soil health through release of compaction and breaking up soil crusts.

4.1.3. Soil erosion

Erosion is much more likely to occur in soil that is not protected by a strong cover of living plants. Both the foliage and roots play important rolls: foliage dramatically reduces the impact force of raindrops on the soil, and therefore the compacting, shearing and other negative effects of rainfall on the soil surface; roots, in turn, help hold soil particles and aggregates in place against surface runoff, and in some soils, sub-surface soil loss.

Compaction is a aggravating factor in erosion as compact soils have lower infiltration rates, poor structure and often poor plant cover, so that less water enters the soil, thus more flows over the surface picking up soil particles that are not protected by well structured soil aggregates or bound by plant roots.

This means that the bare herbicide undervine can be prone to erosion due to the lack of plants and poor soil structure. However, due to the complex nature of soils, for example, the diverse properties of sands, silts and clays, sometimes such compact soils can be less prone to erosion, for example where clays have set hard. However, in situations where undervine, herbicide induced compaction is causing erosion, cultivation the soil with undervine weeders can increase infiltration sufficiently to cause a significant reduction in surface flow and therefore erosion. However, in other soil types, loosening the soil conversely will result in greater erosion. Clearly this effect is site specific and both expert advice and testing on small areas initially are recommended before changing practices across the whole vineyard.

4.1.4. A decade is a short time for a soil

An utterly critical point in terms of understanding the soil system is how slow it is to respond to changes in management. Soil organic matter level is a key driver of many soil processes and a main determinant of soil health, however, levels typically change by a fraction of a percent a year, and with three to five percentage points making the difference between a poor and a good soil, it can take several years for management changes to have an effect.

As many vineyard floor and undervine management techniques affect the soil, e.g. herbicide strips vs. undervine cultivation, the full impact of a change of management can take some three years to show up, especially within the vine and wine. This slow response of the soil systems is also the cause of the over estimation of the benefits of herbicide strips, in that the research demonstrating the benefits was typically conducted only over a few seasons, so the soil was still functioning as if it had a full cover of vegetation. Had the research continued for a decade or more, the effects of soil degradation on plant performance would have become visible. What is now clear, that after long term herbicide, and also undervine cultivation, soil function / health is reduced, sometimes dramatically with resulting impacts on vines and the sustainability of the vineyard as a whole.

4.1.5. Mycorrhizal fungi and soil biology

There is often considerable interest in mycorrhizal fungi among organic producers going all the way back to the beginnings of organic agriculture with Sir Albert Howard writing about the newly discovered symbiosis back in the 1920s. Mycorrhizal science has expanded dramatically since then, however, there is still much to be learnt as researching these fungi is often difficult as they refuse to grow in culture, with many only growing on their hosts, and also studying soil biology as a functioning ecosystem as a whole is also exceptionally difficult.

From what is known, it is clear that mycorrhizal fungi can have a profound effect on plant growth and pest and disease protection, but it is equally clear that the effects can be insignificant, especially in agri / horticultural systems where soil properties are manipulated for the benefit of the crop plant. For grapes it is clear that mycorrhizae are important for both nutrient uptake and suppression of some diseases. Fortunately encouraging mycorrhizae is pretty simple, as a range of other plants share mycorrhizae with grapes, so simply having a range of other species in the vineyard floor, (it does not have to be the undervine area), will ensure an association, or to put it the other way, it is pretty hard to stop vines establishing a mycorrhizal association. The main way to reduce associations is to over-fertilise, especially with nitrogen and phosphorus as easy availability of these nutrients makes it less economic for plants in general to support mycorrhizae so they will expel them and then take up such nutrients direct. Therefore mycorrhizal associations tend to be strongest on lower fertility soils. The second most effective way of reducing mycorrhizae is tillage / cultivation as this breaks up the fine hyphae, so if you are wanting to maximise mycorrhizae then avoiding soil disturbance is key, e.g. mow cover crops instead of cultivating them in. At the same time the direct affects of cultivation on vine roots is likely to have a larger effect, and if, with regular cultivation, the vine's feeder roots 'move' down the soil profile, then the mycorrhizae fungi will simply follow them down, and 'avoid' the cultivation zone.

4.1.5.1. Soil biology

The promotion of soil biology, from microbes to earth worms follows a similar theme to maximising mycorrhizae fungi.

1. First ensure soil nutrient levels and pH are optimum.
2. Use cover crops, both undervine and the mid-row as extensively as possible as keeping soil covered with living plants, especially those that produce and turn over a large amount of biomass, especially roots, has a much bigger impact on soil biology than any of these subsequent techniques.
3. Where cover crops can't be used, use biological / organic mulch, e.g. compost, wood / bark chips, grape marc, grass clippings, etc., however, these are never as good as living plants.
4. Minimise bare soil - whether from herbicides, cultivation or thermal weeding bare soil is highly detrimental to soil biology, with the effect almost entirely due to the elimination of living plants, rather than any form of direct damage to soil biology from herbicides or heat for example.
5. Having said that, cultivation causes considerable damage to all aspects of soil health, so using cultivation to eliminate vegetation has the largest negative effect of all techniques.

See 'Further information sources' for links to additional material.

4.2. Nitrogen: The joker among the nutrients

Nitrogen is unique among the plant nutrients as it behaves quite differently to the others. Also its management is intimately tied up with vineyard floor management. It is therefore vital to have a basic understanding of nitrogen's properties and behaviour to effectively manage it.

The first step to understanding nitrogen and why it is a joker is understanding the three nutrient classes:

- Atmospheric;
- Lithospheric;
- Nitrogen - hybrid atmospheric and lithospheric.

Table 1, shows the main plant nutrients. Between them carbon oxygen and hydrogen make up 96% of plants, but, because they are atmospheric nutrients, i.e., they cycle and are delivered to plants via the atmosphere, they are generally not considered to be nutrients or fertilisers.

Table 1. Proportion of nutrients in plants.

Element	Percent	Element	Percent
Carbon	45	Sulphur	0.1
Oxygen	45	Iron	0.01
Hydrogen	6.0	Chlorine	0.01
Nitrogen	1.5	Manganese	0.005
Potassium	1.0	Boron	0.002
Calcium	0.5	Zinc	0.002
Phosphorus	0.2	Copper	0.001
Magnesium	0.2	Molybdenum	0.00001

In comparison, all the other nutrients except N, represent only 2.5% of the makeup of plants. They are called lithospheric nutrients after the lithosphere, which is the rocks the planet is made from, and the only source of these nutrients, as they don't have gaseous forms,[3] so they cannot cycle via the atmosphere.

Nitrogen is a hybrid - a joker - because the atmosphere is both the main planetary reservoir and the atmosphere is 78% N, the rest being 21% oxygen, 0.93% argon and 0.04% CO_2. The reason nearly all the nitrogen on the planet is in the atmosphere is because atmospheric 'di-nitrogen' (two N atoms bonded together, N_2) is it almost completely chemically inert, so it will not form chemical compounds with other elements so it cannot form rocks. The main reservoir of very other element is the rocks / lithosphere.

The only way di-nitrogen is of use to living things is by it being turned into reactive nitrogen forms (Nr), by fixation. This process requires a very large amount of energy to break the triple chemical bond holding the two nitrogen atoms together. Once separated, then hydrogen, carbon and other elements of life can be bonded with the individual N atoms to made the wide variety of Nr compounds.

Fixing nitrogen is however, such a difficult process, that only a few dozen species of bacteria and archaea can achieve it.

4.2.1. The nitrogen cycle

Figure 1 shows the main components of the nitrogen cycle.

[3] The partial exception to this sulphur which does partly cycle as a gas ($S0_2$), but, it is not the main pathway by which it cycles through the planetary systems, so for simplicity it is ignored in this discussion.

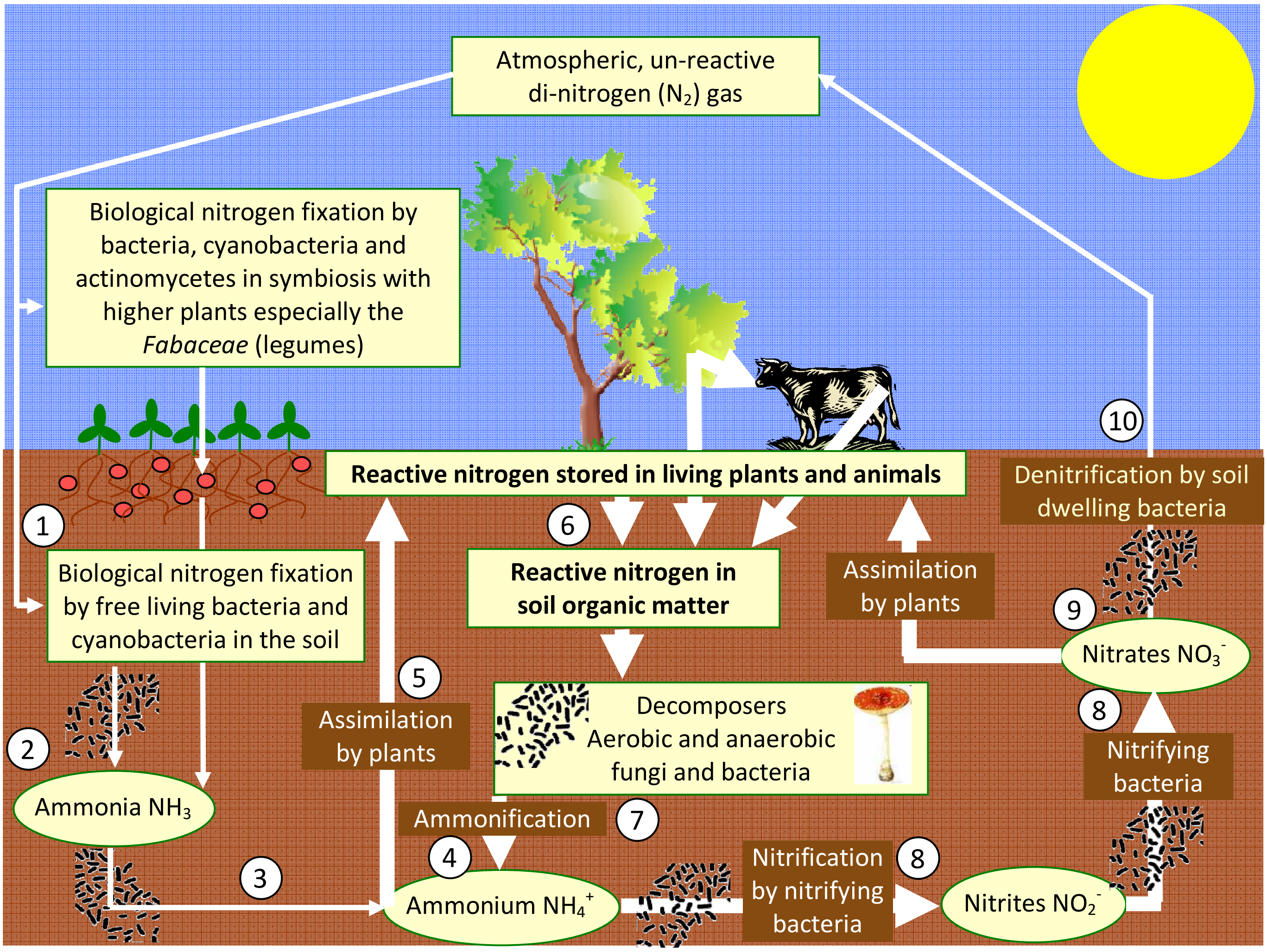

Figure 1. The nitrogen cycle's main components and flows

1. First **atmospheric N_2** is fixed bacteria both free living and in symbiosis with plants such as the legumes.
2. The first form of Nr made is **ammonia** which is one N atom and three hydrogen atoms - the simplest form of Nr.
3. **Ammonia** is then rapidly converted into **ammonium**.
4. **Ammonium** is a key form of soil N: it is one of two forms of N that plants can assimilate / take up, it is also tightly bound to the soil so it does not leach.
5. **Ammonium** that is taken up by plants is then converted into **organic forms of nitrogen (N_{org})**.
6. Plants are then eaten by animals, die, and return to the soil to form **soil organic matter**. Because N does not form chemical compounds with rocks, soil organic matter is the main reservoir of soil N, both as **N_{org}** and as inorganic **Nr**, e.g., ammonium and nitrates that are sorbed onto the organic matter.
7. **Soil organic matter** is then decomposed by bacteria and fungi (this is a key role for soil fungi) and the **N_{org}** is converted into **ammonium**, a process called ammonification.
8. Soil **ammonium** can also be converted into further forms of Nr including **nitrites** which are quickly converted into **nitrates**.
9. **Nitrates** is the other key form of soil Nr along with ammonium. **Nitrates** are also assimilated by plants, but, the opposite of ammonium, they are not bound to the soil and leach easily (when there is soil drainage). This is why Nr pollution of water refers to nitrate pollution, not ammonium pollution.
10. **Nitrates** are also denitrified by other bacteria back into atmospheric **N_2** completing the full N cycle.

4.2.2. The soil nitrogen bank - soil organic matter

As the main reservoir of N in soil is in the form of organic matter, N management and organic matter management are flip sides of the same coin. Soil organic matter, the same as plants (Table 1) is mostly carbon, oxygen and hydrogen with a dash of N.

The main function of N in living things is as part of proteins: nearly all of the N in life is tied up in proteins. Protein is 6.25% N (called the Jones factor), so it is the amount of protein that determines the amount of N in organic matter and biological/organic fertilisers such as compost and fish fertilisers. This means that if a fertiliser is pure protein, its maximum N content has to be 6.25% unless it has been concentrated or fortified.

4.2.3. Nitrogen release from soil organic matter and biologic zero

Leading on from the fact that N is stored as organic matter is that the availability of plant absorbable N (ammonium and nitrate) is therefore largely determined by organic matter decomposition rates (ammonification), which are in turn driven by soil microorganisms, which are in turn driven by multiple factors, which include soil temperature, moisture and oxygen levels. If the soil is too cold, wet and/or oxygen limited, as is typical in early spring, then very little soil nitrogen will be available to plants, especially if a lot of nitrates were leached by overwinter rain. Below 5 to 10°C (an average of 8°C) soil microbes are inactive as it is too cold for their biochemistry to function. This temperature is called 'biologic zero' and is the biological equivalent to absolute zero in physics. It is only when soil warms above 10°C that the microbes can function effectively enough to liberate nitrogen from organic matter through decomposition / mineralisation. This is often why vines are showing N deficiency in early spring, only for it to disappear as the soil warms, as initially the soil is too cold for microbes to release the N stored in organic matter, but as the soil warms, lots of N is released.

4.2.4. Nitrogen fixation and biologic zero + available soil N

Likewise, as nitrogen fixation in the legumes is undertaken by bacteria, 8°C is the lower temperature at which fixation takes place, and only very slowly at that. Optimum N fixation occurring between 20°C and 30°C. Therefore in most of New Zealand, the overwinter soil temperature is too cold for nitrogen fixation, so even if legumes are grown as a green manure over winter to fix nitrogen, it is likely that none will be fixed till late spring.

Legumes also only tend to fix N if there is insufficient amounts of available N in the soil. This is because fixing N is a very energy intensive process (due to the physics of chemical bonds) so legumes don't waste energy if they can get N from the soil.

4.2.5. Cultivation and soil nitrogen

As noted above, soil oxygen levels are critical in determining the release of N from soil organic matter. A key effect of cultivation is to introduce oxygen into the soil, and also often warm it up by exposing more soil to the warmth of the atmosphere. The result of this can be that a considerable amount (e.g., 20-40 kg N/ha) of available N is released by cultivation. This can occur in both the undervine, from weeding activities and also the mid-row from cultivation. However, this effect is dependent on their being sufficient, easily mineralisable organic matter present in the cultivation zone. If cultivation is used on a regular basis, easily mineralisable organic matter can be quickly depleted leaving only more recalcitrant forms such as humus, so that the N release effect of cultivation disappears. Therefore to be effective, cultivation has to follow actively growing plants that replenish the easily decomposable soil organic matter fraction.

This highlights the difference between total and available N as determined by soil tests. Total N is a function of the total amount of soil organic matter, while available N represents the easily decomposable fraction of organic matter plus the inorganic / mineral forms of N, ammonium and nitrate.

4.3. The vine system

Thanks to the long tem global popularity of wine, grape vines are a very well understood crop having been the focus of much viticulturalist and scientific investigation. There are therefore many excellent handbooks explaining the details of vine functions, so only the key points relating to vineyard floor management will be covered here.

4.3.1. Roots

Vines, in common with other perennial woody crops, have shallow feeder roots near the soil surface, compared with annual crops and weeds where the feeder roots penetrate the bulk of the soil. This is because, in their natural state, woody perennial plants typically exist in woodlands / forests, and vines in particular can only exist where there are other large perennial plants for them to climb up. In such ecosystems the nutrients cycle through the leaf litter, so the main nutrient source is the leaf litter on the soil surface. Perennial crops therefore have evolved shallow feeder roots to capture this nutrient flow, while in comparison annual plants have evolved feeder roots that penetrate the soil bulk as they grow on disturbed ground where nutrients and water are distributed throughout the soil profile. For perennial species, especially those evolved in temperate climates with pronounced seasonal variation in soil moisture levels, they also often have roots that will penetrate to considerable depth in search of water. These roots have a limited role in absorbing nutrients as typically there are very few plant available nutrients beyond the first 30 cm depth of soil, and in undisturbed soil, 90% or more plant available nutrients are within the top 5 cm - the biologically active zone where oxygen can easily penetrate.

Vine roots respond and can adapt to vineyard soil conditions. As described above, compaction can prevent them accessing the mid-row. Where undervine cultivation is used, this can result in the vines 'moving' their feeder roots below the depth of cultivation, while the opposite can occur when biological / organic surface mulches are used where the feeder roots will grow into the mulch. The upper extent of this adaptability is not well established, but, within woody perennials the flexibility can be considerable, for example in agroforestry systems the trees can 'move' their roots downwards by a meter below the root zone of the annual crops grown between them (Briggs, 2012).

Because vines (and other perennial woody crops) have shallow feeder roots, this is why, despite their size they can suffer significant competition from comparatively small annual weeds, particularly grasses due to their highly competitive fibrous root systems. A clear example of this was demonstrated in an organic high cane blueberry crop (high cane = ~2 m tall plants) in California, USA, infested with either Californian thistle (*Cirsium arvense*) or couch / twitch grass (*Elymus repens*): despite the thistle growing up through the bushes and competing for light, it had no effect on the crop and conversely, while the grass was well overtopped by the bushes, it caused a 20% reduction in height and an even bigger yield loss. This was because the root system of Californian thistle grows at depth, typically 20 cm or more, and send only shoots up through the blueberry feeder roots without competing with them, while the grass, with its competitive and shallow fibrous feeder roots competed very strongly with the blueberries, causing the large growth and yield reductions.

This illustrates the potential for undervine cover crops that have root systems that do not compete with the vine roots and therefore provide all the benefits of cover crops (e.g., soil protection, weed suppression) without reducing vine productivity. However, very little research has been done in this area, so little good data exists.

4.3.2. Rootstocks

A range of different rootstocks are used in viticulture for a range of reasons including pest tolerance (e.g., phylloxera), and controlling scion vigour, which in turn has large effects on grape yield and quality. The rootstocks themselves therefore vary considerably in how vigorous they are, with some having aggressive root systems that can effectively compete with weeds, while others are highly susceptible to competition. Rootstock vigour in turn interacts with soil 'vigour', so matching scion, to rootstock and soil properties is one of the most critical decisions of vineyard establishment. However, undervine management, whether bare ground from herbicides or cultivation or using undervine living or dead mulches, adds another variable to the soil-rootstock-scion interaction. This can be both a benefit and hindrance, as different undervine (and vineyard floor) management approaches can be used to both increase and decrease vine vigour, and associated grape and wine quality. This also highlights the need to consider undervine management system when deciding on rootstocks, e.g., choosing a more vigorous rootstock where the undervine will be vegetated.

4.3.3. Critical competition periods

As a summer active, deciduous species, vines have periods of active growth and dormancy. When the vines are dormant over winter, there is effectively no interaction / competition with other plant species growing in the undervine or mid-row so a wide range of plants can be grown overwinter with no immediate direct impact on the vines. However, the indirect flow on effects can be considerable - both positive and negative, e.g., improved vine vigour due to increased N from legumes or N lock up from growing cereals. In comparison, when the vines are in active growth, particularly in the first half of spring / summer, they are potentially highly susceptible to competition, both for nutrients and water, and other parts of the annual vine cycle may also be critical times for competition.

This means that having the same undervine and mid-row management system throughout the year may not produce the best results, for example, overwinter, a competitive cover crop could be grown to out-compete weeds, which is then eliminated in spring before the start of vine growth, with a weed-free undervine maintained until véraison to minimise vine competition, then a less competitive summer annual legume could be established at véraison to fix nitrogen, which is in turn undersown with the competitive winter cover crop.

4.3.4. Competition at establishment and changes as vines age

Like all woody perennial crop species, vines are particularly susceptible to competition when young, typically in the first two to three years post planting. After this period the vines have built a sufficiently large and robust root (and foliage) system that they can withstand competition without large adverse effects. However in the first two to three years, competition can dramatically restrict vine growth, even kill them in extreme cases, so for the first few years after planting, competition from other plants typically has to be eliminated.

While established vines are less susceptible to competition, this is not to say that an understory or mid-row management system that works for a young (e.g., less than ten years) vineyard would be suitable for older vines (e.g., greater than 20 years). For example, in the earlier years of a vineyard, the vines and the soil may need more nitrogen so more extensive use of nitrogen fixing legumes could be made, while as the vineyard matures, and soil nitrogen levels have built up, excess vigour may be an issue, in which case, legumes should be eliminated and the undervine planted with species aiming to lightly compete with the vine roots. Therefore vineyard floor management needs to be tailored not only to the terroir and rootstock / scion combination, but also the age of the vines as well.

4.4. The non-vine plants - weeds and non-crop plants

As discussed in the introduction (section 3.3), the concept that once a weed, always a weed, is being consigned to history. However, regardless of whether non-vine plants in the vineyard are true weeds (causing real and actual harm) or non-crop plants (not causing harm), there is a range of critical pieces of knowledge required to be able to effectively manage them, these are:

- The plants morphology: short vs. tall, competitive or uncompetitive roots, etc.;
- Its lifecycle / reproduction: annual, biennial, perennial;
- Spread / dissemination;
- Response to mowing, cultivation and thermal weeding;
- Ecological interactions;
- Pests and diseases.

4.4.1. Morphology - root structures

There are a wide range of morphological attributes of weeds that are important for annual cropping (e.g., plant height) but these are of limited consequence in viticulture as most weeds are shorter than the vine canopy. The key morphological attribute for viticulture is the root morphology.

As described in section 4.3.1 on vine roots, different plants have quite different competitive effects on crops. The grasses, with their fine, fibrous root systems are highly competitive and very effective at exploring the majority of the top 20 cm of soil. This is why even small grass plants, and the couch described in section 4.3.1, can be highly competitive. In comparison, the tap roots of dicots tend to have fewer roots at the soil surface but penetrate deeper. In addition, the legumes often have the least competitive root systems, partly because they can 'manufacture' their own nitrogen ‘fertiliser’ so they don’t need to extract it from the soil.

4.4.2. Lifecycle

In organic / non-chemical weed management, understanding a weeds lifecycle it utterly critical for its effective control. The first major divisions is among the annuals, biennials and perennials.

The life strategy of a perennial weed is for the plant itself to survive as long as possible while in comparison the life strategy of annual and biennial weeds is to survive as a seed as long as possible, with the plant itself only being a transient stage in this strategy. This means that the management strategy of perennials has to focus on the plants, while the strategy for annuals and biennials is to focus on the weed seed bank, i.e., the reservoir of weed seed within the soil. This approach is the origin of the cropping farmers adage ‘one years seeding, seven years weeding’. This is often the critical failure of herbicide and mowing or tillage based weed management strategies, in that annual weed control is targeted at the periods of critical vine competition, which then lapses at other times of year. This results in weeds setting seed, often prolifically, thus creating a bigger and bigger weed seedbank making control in future years harder and harder. The foundation of effective annual and biennial weed management is preventing the ‘weed seed rain’ i.e., preventing weeds setting ripe / viable seeds which drop to the soil, and thus replenishing the weed seed bank. This includes all weeds on the vineyard floor, not just in the undervine area, so management of the mid-row is as critical as the undervine area.

4.4.3. Spread / dissemination

Related to reproduction is how weeds spread / disseminate. For annual and biennial plants spread is almost exclusively by seed dispersal. While plants / weeds have some very impressive means of dispersal, contrary to popular belief, nearly all annual and biennial weed seeds fall within a meter or so of the parent plant, which is why weed infestations are so patchy. Only a few seeds are spread any distance, and even less between vineyards / fields, so normally such dispersal is of no importance as the resident weed seed bank dwarfs the inter-vineyard seed traffic. The only exception is for weeds that are is entirely absent from a vineyard, especially creeping perennials, and in such cases preventing inter-vineyard dispersal of such weeds should be a key control tactic.

The perennials, can be divided into two types, the creeping and static. Static perennials, such as docks (*Rumex* spp) generally only disperse by seed, so management of their weed seed rain is key to managing their spread within a vineyard. Creeping perennials e.g., Californian thistle, couch grass, buttercup (*Ranunculus* spp), and field bindweed (*Convoluvus arvensis*), spread by vegetative growth, typically through horizontal roots or stems (stolons and rhizomes), and seed production may be limited or non-existent. Non-chemical control of such weeds can be particularly difficult, especially where the creeping structures are deep in the soil, such as the roots of Californian thistle.

4.4.4. Response to mowing, cultivation, and thermal weeding

The knowledge on how a herbicide kills a weed resides with the biochemist, so, growers are in effect buying 'bottled knowledge' when they use a herbicide. In contrast, with non-chemical weed management, there is no equivalent of the knowledge contained in bottles of herbicide, rather the knowledge of how to physically kill a weed has to reside in the growers head.

4.4.4.1. The bud based perspective

The core piece of that knowledge is that that plants can only grow (in the scientific meaning of cell division, rather than ‘merely’ expanding cell size) from their meristems (buds), as this is the only undifferentiated (stem cell) tissue in plants. Meristems only exist in the root tips, in shoot buds and in the cambium layer around stems and in the middle of roots. To physically kill a plant it has to be prevented from regenerating from its meristems. This knowledge is effectively the flip side of vegetative plant propagation: i.e. to propagate a plant (e.g. by two node cuttings, or root cuttings) you have to know how to get it to produce new roots or shoots. Flipping back over, for weed control, you need to know what powers of regeneration, e.g. production of roots from shoots, or shoots from roots, any given weed has, as that determines what it will take to kill it. This ability to produce roots from shoots and/or shoots from roots is called dedifferentiation.

The majority of annual and biennial plants have limited powers of dedifferentiation as their evolutionary strategy is to 'be a seed' not a growing plant. It is mostly the perennials that can dedifferentiate and, these plants are the hardest to physically kill as even small parts of the weeds, e.g. root fragments or stem nodes, can regenerate entire plants.

4.4.4.2. How the bud based perspective informs weed management

For 'simple' weeds with no dedifferentiation ability, severing them at or near the hypocotyl, i.e., the junction between the true shoot and true root systems, will kill them outright as this separates the water and nutrient gathering roots from the photosynthesising shoots and leaves. For species that can regrow shoots from roots, they will simply re-grow the shoots, and species that can regrow roots from shoots, if the shoots are left in such a position they can re-root, e.g. partly buried in moist soil, they can also regrow. Controlling these weeds is explained in more detail below.

Mowing and thermal weeding (flame or steam) are very similar from the bud based perspective. Both methods remove / destroy only the above grown foliage / buds. For ‘simple’ weeds, if mowing or thermal treatment destroys the weed down to the hypocotyl, then it will kill the weed. If the weeding treatment does not reach the hypocotyl the weeds can regenerate from the remaining buds, but, how quickly and completely they regenerate depends on the location of the buds, which is divided into two groups:

- All buds are at or below ground level i.e., pasture species
- Most buds are above ground level i.e., cropping species

The thing that makes a pasture species a pasture species (both sown plants and weeds) is that all its buds are at or below ground level, for example, grasses, white clover, plantain, yarrow, docks, rushes, buttercups, dandelions, daises, etc. The reason their buds are at ground level, is that buds are expensive 'real estate' for plants. Leaves are mostly water, while buds are dense clusters of very small but nutrient packed and actively dividing cells. For a plant, leaves are therefore cheap and expendable, buds are high value and are lost at considerable cost. By having their buds at or below ground level, pasture species ensure that their buds are protected from grazing, mowing etc., and that only leaves are lost, which are cheap to replace. In comparison, if a 'cropping species' plant, i.e., one that has stems growing upward, with buds in every leaf axil, looses its above ground structures, then it requires a lot of root reserves to replace them, and if defoliation occurs more than a few times, the plant typically runs out of nutrient and energy stores and dies.

Frequent defoliation or disturbance is also a key way to mechanically or thermally control perennial weeds and those that can dedifferentiate, i.e., the plants are broken up, or robbed of their foliage sufficiently frequently that they die of exhaustion. The number and frequency of passes varies considerably depending on the size of the plant, its species, time of year, etc., and the only way to determine this for any given vineyard is to work this out in situ.

4.4.4.3. Ecological interactions

Ecology is the science of how species interact with each other, and understanding the interaction of plant species within a vineyard and the interactions of plants with management techniques is critical to effective vineyard floor and undervine management.

The example above of the difference between pasture and cropping species responses to defoliation, explains why, if mowing or thermal weeding is solely, and repeatedly, used for weed control the plant species that quickly become dominant are pasture species, as it is only they can withstand regular defoliation which quickly kills cropping species.

Conversely, where cultivation is used, the regular soil disturbance favours cropping weeds, as they are pioneers of disturbed ground, emerging from the weed seed bank when ever conditions are suitable, with the most suitable conditions being soil disturbance and the destruction of existing vegetation.

Looking at plant interactions (in the absence of human interventions) there are two main issues:

- The level at which plants compete or can co-exist
- Plant succession

Plants compete both above and below ground. Below ground root competition is often underappreciated, due being out of sight and out of mind. However, as the example of couch and Californian thistle infesting a blueberry crop showed (section 4.3.1), root competition can be significantly more important than foliar competition.

Plant species therefore vary considerable in how much they compete with each other. Plants with similar growth, e.g., two pasture grasses, are strongly competing for the same soil and also for above ground space, so they compete very strongly, while a deep rooting and tall open legume, such as lucerne and a pasture grass only compete weakly, especially as the legume can fix its own nitrogen.

This variation in competition and co-operation is critical when selecting mixtures of plant species for use in a vineyard, especially when using mixtures in the undervine, as the vine itself is the most important component of the plant mixture.

Left to themselves, over sufficient time, plants undergo succession, i.e., the types of plants growing in a location change, starting with the cropping species that are adapted to open and disturbed ground, which are followed by the perennial pasture species, that crowd out the cropping species and eliminate the open soil they need for establishment, and finally pasture species are replaced by woody perennials, that shade out the pasture species. Therefore, to maintain annual / cropping type species, perennial vegetation has to be periodically removed, while to maintain perennial pasture species, regular mowing or judicious thermal treatments are required, and if no management is implemented at all, then woody perennials, e.g., gorse, broom, blackberry, will start to arrive. Plant succession therefore has to be actively managed if vine growth objectives are to be achieved.

Allelopathy

Allelopathy is a biological phenomenon by which a plant produces one or more biochemicals that influence the growth, survival, and reproduction of other plants. These biochemicals are known as allelochemicals and can have beneficial (positive allelopathy) or detrimental (negative allelopathy) effects on the target organisms, which can include other plants, but also pests, diseases and herbivores. Within agri/horticulture allelopathy mostly is used to refer to one plant species (crop or cover crop), that reduced the germination and/or growth of another species, (often weeds). While allelopathic effects can be quite profound, e.g. the leaf litter of some tree species can eliminate all understory vegetation, in a horticultural situation such as vineyards, separating out allelopathic effects from competition is impossible in the field and requires sophisticated controlled condition experiments. Also at a practical level, whether two species are interacting through competition, allelopathy or a mixture of both is often immaterial as the end result is the same. So while allelopathy is a real and important biological effect, its relative importance is often overstated in a production situation.

4.4.5. Pests and diseases

Planted or useful non-crop plants within the vineyard need to be actively managed as a ‘crop’ in their own right, to get the best out of them. If they are planted and forgotten they are unlikely to perform. Many of the plants used are well known crop and/or pasture species and they can be as susceptible to pests and diseases in the vineyard setting as when they are grown as cash crops in their own right. Worse, if they are grown year on year without the rotation as used in arable cropping and horticulture, they may become more susceptible to pests and diseases. A good example of this is in the European Union, where on-farm wildlife mixes are often grown in the same locations every year, to simplify support payment verification, but which dramatically underperform because of the lack of rotation (Leake *et al.*, 2011).

There is therefore a need to consider potential pest and disease problems that may build up though continuous use of the same species and plan to build diversity into the system to prevent this.

Non-vine plants must also be assessed to determine if they are alternative hosts for vine pests and/or diseases. Generally such species should be avoided unless there is a particular advantage to have such a species, e.g., they allow the pests predators to proliferate and therefore keep the pest below economic thresholds.

4.4.5.1. Conservation biological control

The deliberate use of non-vine plants to provide 'conservation biological control' for vine pests and diseases is considered a key nexus for the future of viticulture (as introduced in section 3.2). A highly successful example of this is the 'Greening Waipara' project where buckwheat (*Fagopyrum esculentum*) is planted in vineyards to provide nectar and pollen, to boost the population and fecundity, of an already present, parasitic wasp (parasitoid) of leafroller caterpillars, such that the caterpillars population is brought under the economic control threshold, often much lower (Burzynska, 2013). As a range of non-vine plants are being used for other purposes in the vineyard (soil protection, nitrogen fixation, etc.) then choosing plants that can also provide conservation biocontrol services, starts to create a multifunctional system that is a true nexus.

Another key benefit of conservation biocontrol is that it is mostly immune to the evolved resistance that is an increasing issue with agrichemicals, because it is using biology to control biology, so if the pest starts to out-evolve the biocontrol organism, then the biocontrol organism will in turn evolve to neuter the pest's evolution - i.e., an arms race / Red Queen hypothesis [4]. In comparison, agrichemicals are a static / non-evolving solution so they can't adapt to an evolving pest, hence why pests become resistant.

However, providing detailed examples of conservation biocontrol systems is beyond the remit of this booklet.

5. Turning theory into practical vineyard floor management

The previous chapter gave an overview of the key components and functioning of the vineyard floor system. This theory then needs to be turned into a vineyard floor management system. The key point is that there is no one or no 'perfect' solution. Every vineyard has to create a management system based on its soils, climate, vines and production objectives, that also evolves over time and changes in response to how the system evolves over time.

Typically, the management of undervine area will be different to the mid-row, because they generally have different impacts on the vines:

- **The undervine** is the area where typically most of the vines feeder roots are present, and where irrigation is used, where most, if not all of the water is applied. Management of this area therefore has large impacts on vine performance.
- **The mid-row** typically has a lower volume of vine feeder roots, due to the compaction caused by tractors makes it harder for feeder roots to penetrate, plus the grass sward typically covering the mid-row strongly competes with vine roots. Depending on soil type, levels of compaction, if compaction remediation is used and soil moisture status , the deeper water gathering roots may or may not penetrate the mid-row. Activities in the mid-row therefore typically have lower, or even no, direct impact on immediate vine performance.

5.1. The undervine

There are five primary organic / non-chemical undervine management approaches:

- Cover crops / living mulches;
- Mulches - both organic / biological materials and sheet materials e.g. plastics;
- Mowing;
- Thermal weeding;
- Cultivation (tillage).

[4] wikipedia.org/wiki/Red_Queen_hypothesis

Firstly, these are not mutually exclusive techniques, e.g. biological particulate mulches (e.g. pine bark) can be supplemented by thermal weeding, or cover crops could be used over-winter and then destroyed in spring using mowing or cultivation.

Next, the approaches at the top of the list are typically the most ecologically beneficial and environmentally sustainable, while as you go down the list they become less ecological and sustainable, as 'plant power' gives way to fossil fuel power, increasing levels of soil disturbance and higher direct costs. However, counterbalancing the positive benefits of cover crops and mulches are the practical complexities of managing them to ensure optimum vine performance, compared with mowing, thermal weeding and cultivation which are simple, reliable point interventions that typically have rapid effects on the vines. So while it would be ideal from an ecological and sustainability perspective to use cover crops and mulching, they are often harder to implement, and mowing, thermal weeding and cultivation are useful backstops.

The following sections explain the key management aspects of each technique.

5.2. Cover crops, green manures and other 'non-cash crops'

The terms 'cover crops' 'green manures' 'and many related ones such as 'catch crops' and 'living mulches', don't have agreed definitions. They all however describe 'non-cash crops' i.e., crops grown for a purpose other than generating a direct cash income. Internationally 'cover crop' is the umbrella term for all such crops and in some countries, e.g., the UK and NZ, green manures are used to refer to nitrogen fixing crops and catch crops refer to cover-crops grown to reduce nutrient, especially nitrogen leaching. Rather like the many different names used, cover crops have a multitude of different uses and objectives. Some of the key ones are:

- Increasing soil organic matter / soil carbon;
- Protecting the soil surface, particularly from erosion;
- Improving soil 'fertility' e.g., fixing nitrogen, increasing available phosphorus, increasing cation exchange capacity via increased soil organic matter, reducing nutrient leaching, etc.;
- Improving soil health / quality, such as soil structure, principally as a result of increased soil organic matter;
- Improving drainage and water holding capacity, as a function of organic matter, and macropores resulting from dead root holes and earthworm burrows;
- Suppressing weeds;
- Managing pests & diseases (conservation biocontrol);
- Increasing biodiversity and increasing (non-harmful) wildlife.

Many of these objectives are now viewed as key components for addressing global environmental issues, such as climate change, while others are more clearly focused on short to long-term benefits for the production system itself, e.g., nitrogen fixation. The key thing is that although they are all non-cash generating crops, most aim to improve the overall profitability of production systems in the long-term. They therefore represent an investment in the vineyard with an expectation of a positive return on investment in future years, so should therefore be treated in accounting terms, the same as any other form of investment. The are definitely not 'luxury' or 'nice to have' items, that can be dispensed with if finances are tight.

The diversity of cover crops and vineyard systems also means that it is impossible to provide more than an introduction and highlight the key issues in this handbook. A number of additional information sources are therefore provided in section 10.3, some of which are vineyard specific.

The following sections give both a general introduction to cover crops and specifically their use in the undervine. The chapter on the mid-row (section 7) deals with the issues regarding the use of cover crops specific to the mid-row area.

Using cover crops in the undervine area is the most technically challenging due to the interaction of the vines and cover crops, but when it works, it can be highly effective and one of the cheapest management options, e.g., compared with mechanical weeding. Therefore if using undervine cover crops has the potential to work for a given vineyard, it is worth expending significant time trying to make it work, as the long-term payoffs can be considerable.

The following sections highlights the main issues that need to be considered when using undervine cover crops.

5.2.1. Competitive interaction

Fundamentally, using cover crops undervine is about managing the ecological / competitive interaction between the cover crop and the vine plant. As most vine training systems have the foliage above the height of all but the very tallest cereals (exceptions being rye and triticale) above-ground competition is zero for most cover crops. However, as noted in section 4.4.4.3 belowground / root competition often has the greatest competitive effect and it can be unrelated to above ground foliage size. What is important is if vine and cover crop roots are likely to share the same soil area or not and if so which root system is going to dominate the below ground battle for soil and nutrient resources.

Having a cover crop compete with the vines is not always a bad thing. In highly production terroirs (fertile soils, lots of soil moisture) vines may well be over-vigorous. In such situations, having a cover crop that competes with the vines and reduces vigour has the potential to reduce costs associated with vigour control through foliar management, e.g. trimming.

5.2.2. Timing: vine dormancy and growth

Cover crops do not have to be grown all year round, nor do the same crops have to be grown all year. When vines are dormant over winter, there is effectively zero immediate competitive effect as the vines are inactive. Therefore cover crops that could have large competitive impacts on the vine during spring and summer (e.g. cereals) could be grown over winter. Cover crops for use over summer typically need to be less competitive species to avoid restricting vine growth, even on overly vigorous vines.

5.2.3. Residual ‘competitive’ effects - nitrogen robbery and soil moisture

While vines are not susceptible to competition while they are dormant, growing a highly competitive green manure over winter and then killing it before vines break dormancy, does not completely eliminate the effects of cover crop on the vine. While it will eliminate immediate and direct root competition, the cover crop can have a large impact on soil conditions, especially around soil water and most critically soil nitrogen.

Overwintered cereals and other species, e.g. mustard, can take up considerable amounts of soil nitrogen over winter - figures of 50 to 100 kg N/ha are not uncommon (though this amount is very variable and depends on the amount of available soil N, the cover crop species, soil type, water status etc.). This N is then ‘locked up’ in the roots and foliage of the cover crop, and it cannot be released until the cover crop is not only killed but when it decomposes and the N within the plant residues is released. Decomposition can take quite some time, especially in cold soils in spring, and it almost stops if soils are dry, so it can take weeks even months for the N to be released back. This is referred to as ‘nitrogen robbery’ a term that is more commonly associated with the incorporation of high carbon biological residues (e.g. straw, woodchip, etc.) into soil resulting in soil microbes using up available soil N to decompose the high C residues. The amount of available N locked up with a strong N retaining cover crop can be close to 100%. In overseas arable cropping systems using overwintered cover crops, research indicates that for non-legume cash crops it is vital to have more than 50% or more of the cover crop as legumes to ensure sufficient N supply for the following crop, while if a legume cash crop is grown, it is OK to have zero legumes in the cover crop mixture. It is clear from this that growing undervine, overwintered cover crops is complex, so initial small trial areas are highly advisable.

The effects on soil moisture of cover-crops grown during vine dormancy varies considerably. In some situations, using cover crops can increase residual soil moisture after their destruction by the resulting mulch reducing surface loss, in other situations, the cover crop has used up soil moisture over winter, resulting in less being available in spring. Long term use of cover crops will also improve soil moisture storage capacity through increased soil organic matter while also improving soil drainage reducing waterlogging. The impacts of cover crops on soil moisture both short and long term are therefore highly specific to individual vineyard situations and can be difficult to predict.

Another residual effect can be due to the allelopathic effects of some cover crops, however, as noted in section 4.4.4.3 disentangling this from straightforward competition and other residual effects is difficult and in general, inter-plant allelopathy is stronger against seeds and seedlings rather than established plants such as vines.

5.2.4. Nitrogen fixing vs. nitrogen dependent cover crops

Related to both competition and also timing around vine dormancy vs. growth, is the contrast between nitrogen fixing and nitrogen catch crops (see section 4.2 for full details on nitrogen). Within a vineyard, and especially the undervine, nitrogen fixing cover crops are mostly limited to the legumes (Fabaceae) that are used as agricultural crops or pasture species, such as the clovers, lucerne, peas, beans, and lupins. Nitrogen catch crops are therefore everything else.

The fixation of atmospheric nitrogen by legumes in a vineyard, (both undervine and mid-row) can be a positive and a negative. In over-vigorous vines, supplying more N is highly likely to make them even more vigorous, and conversely, where vines are struggling due to low soil N, newly planted vines that need a nitrogen boost etc., are likely to benefit from the extra N, especially if other means of supplying N are restricted, e.g. by organic standards.

As discussed in section 4.2, nitrogen cannot be fixed below biologic zero (~8°C) and it is not until soil temperatures are quite a bit higher than biologic zero, that significant amounts are fixed. Therefore little or no N fixation occurs over winter, and for overwintered green manures, the majority, e.g., 80% of the N that is fixed may be fixed in the last two to three weeks of the crops life in spring. Therefore leaving such crops as long as possible ensures maximum N fixation.

Legumes, even when the N they fix, boosts vine growth, they can still directly compete with the crop and thus have a negative effect. Having said this, legumes generally have some of the least competitive root systems, as they have the advantage of being able to make their own N, so they don't need to compete for soil N with other plants, and in relation to vines, the most legume cover crops, have tap roots that explore the soil bulk, so there is less potential for interaction with vine surface feeder roots, the exception being white clover (*Trifolium repens*) which is stoloniferous and shallow rooted.

5.2.5. Cover crops are crops - and need to be managed as a crop

As the name implies, cover crops are crops - indeed most of them are grown as cash crops somewhere in the world and they have been selectively bred for production. They therefore need to be looked after as well as any cash crop, as sowing and forgetting them is likely to result in them underperforming, potentially significantly, compared to when they are well managed.

There are four key components of their management than require attention, and these also relate to how the cover crop and vine interact / compete. These are:

- Establishment
- Water;
- Nutrients;
- Pests & diseases.

5.2.6. Establishment

To achieve optimum establishment, most cover crops will need to be drilled into the soil (rather than just broadcast on the surface), and they will also need existing vegetation controlled, i.e., through herbicides or cultivation. Requirements will vary, with small seeded species needing to be sown shallow while bigger seeded types should be sown deeper. In general, you should follow the establishment guidelines for the species when it is grown as a cash crop.

5.2.7. Competition for water

Cover crops can require considerable amounts of water because they are quick growing annuals and most of that water comes from the top half to one meter of soil as many are shallower rooted annuals, compared with deep rooting perennial vines. The use of cover crops may tip a vineyard that does not require irrigation over the point to where irrigation is required, both for the cover crop and vines, and where irrigation is already required for the vines, considerably more water may be required by the combined needs of vines and cover crop. The type of irrigation, e.g. drip line vs. sprinklers may well interact with the cover crop - vine system. For example, shallow rooted grasses spread over a meter width of undervine area may simply be unable to access water flowing out of a driptape which mostly soaks vertically, rather than laterally into the soil. Clearly changing irrigation application from drip line to sprinklers is a significant capital cost, however, if the undervine cover crop is providing sufficient return in the other services it provides, such infrastructure changes may be profitable. There is also growing interest in buried irrigation tape, as this helps keep the soil surface dry reducing weed emergence, but, this may also make establishment of cover crops harder and limit them to deeper rooted species.

5.2.8. Competition and requirement for nutrients

Many cover crops are quick growing annual arable and horticultural crops, and as such they can have a high demand for soil nutrients, especially nitrogen, phosphorus and potassium (NPK), and they are also often sensitive to pH. This nutrient demand profile may be different to that of the vines, both in the amounts and their distribution across the growing season. It is therefore important to take into consideration these different and cumulative nutrient demands and ensure that they are being addressed, otherwise the potential for competition between cover crop and vines for nutrients is likely to be exacerbated.

5.2.9. Competition with weeds

Getting a cover crop to out-compete weeds while not causing excessive competition with the vines is not straight forward. Cover crops that can achieve this need to have root systems that don't compete with the vines roots (assuming the cover crop’s leaves cannot reach the vines foliage) but that has very competitive foliage that can smother weeds, and/or compete with the weeds roots. As noted before, due to little research having been conducted, few recommendations exist.

5.2.10. Frost

Cover crops can affect the frost incidence in a vineyard by affecting heat radiation between soil and air, both the warming of the soil from the air during the day and warming of the air by the soil at night, principally due to the insulating effect of the cover crop, but also potentially through reduced / changed air movement, water loss effects on humidity and increasing the populations of ice-nucleating bacteria (*Pseudomonas syringae*).

The amount of research of managing cover crops for vine frost risk (both undervine and mid-row), is limited but from the international work undertaken, it is reasonably clear that the best approach is to mow the cover crop close to the ground. Cultivating the crop into the soil has the advantage of further reducing the insulating effect of the crop and its residues on the soil, but, the cultivation itself then increases the amount of air in the soil which increased its insulating effect, the net result being that cultivating in residues and low mowing had the same effect and both were similar to bare soil for frost protection.

While it is possible to modify the amount of *Pseudomonas syringae* on vine leaves and therefore the degrees of frost before ice forms, the total global research on manipulating *P. syringae* for frost management on all crops is very limited and therefore not currently considered a reliable option.

5.2.11. Cover crop species and types

There are a wide range of plant species that can be used as cover crops in vineyards. These include the cereals, pasture species including both grasses and forbs (herbs) such as chicory and plantain, seed crops such as mustard, buckwheat and phacelia, naturalised vegetation and also native plant species. Rather than dividing up cover crops by species or agricultural use, it is more helpful to segment them by their attributes, the primary aspects of which are:

- Annuals & biennials, or perennials
- If the active growth stage is in summer or winter, or year round.
- For annuals and biennials, if they self perpetuate, e.g. establish a seed bank, or have to be re-established every time.
- Nitrogen fixing or nitrogen catching
- Size / competitiveness of above-ground foliage
- Size / depth / competitiveness of root system

Due to the large number of cover crop species available, it is not possible within this publication to list them or more importantly, describe their key attributes. However, there are a number of good resources that already provide such information, both more general and with an international focus and those more specific to wine production. See section 10.3 at the end of this booklet for information sources.

5.3. Mulches

There are two main categories of mulches for undervine management:

- Sheet mulches;
- Particulate mulches.

Sheet mulches are traditionally made of plastic, both impermeable and permeable, and also other materials such as paper. These products are widely used in vegetable production and amenity horticulture, however, their use in viticulture is limited as the cost is generally not justifiable in terms of economic returns, they can interfere with other actives, e.g. mowing the mid-row, and their lifespan is often a few years, which compared to the potential decades lifespan of a vineyard means they are only a short term solution. They can also have negative effects on soil biology, principally through preventing plants growing in the undervine area - which is their primary purpose - and they also prevent the application of solid fertilisers both mineral and organic / biological (e.g. compost). Their practical application is therefore considered to be limited so they will not be covered any further.

In comparison, particulate mulches have greater potential but also downsides. There are a wide diversity of particulate mulches, but the first major division is between non-biological (inorganic) and organic / biological.

5.3.1. Non-biological particulate mulches

Non-biological, particulate mulches, (e.g., stones, sea shells, crushed glass) have been used in vineyards, probably back to the beginning of viticulture. The key attribute of non-biological mulches is their permanence as they don't decompose, so they persist longer than biodegradable mulches.

Their main effects benefits include:

- Increasing soil moisture by reducing evaporation from the soil surface, the size of this effect depends on both the particle size and depth of mulch, with larger particles such as stones allowing greater air movement and therefore more evaporation than smaller particles. The greater the depth the lower the water loss.
- They help protect soil surface structure from the effects of rain and irrigation impacts, and may therefore help improve water infiltration.
- Mulches also have the potential to reduce weeds / undervine plant growth. However, the often profound ability of weeds to establish in the most inhospitable of situations mean that sooner or later the mulch will be invaded, either from plants establishing from the weed seed bank under the mulch, from seeds that land on the mulch or perennial creeping plants that grow into the mulch.
- Highly reflective mulches can also effect the lower levels of the vine canopy by reflecting light into it, a process that could be both beneficial and unhelpful depending on the vine system and wine objectives.
- Mulches can also moderate soil temperature, i.e. cooler in summer and warmer in winter, while at the same time they;
- Can change the temperature of the canopy by acting as a ‘heat bank’ storing heat in the day and releasing it at night, although the size of this effect will vary a lot between different materials and particle size, e.g. rocks vs. ground glass.

All these factors can have impacts on the vine and through to wine quality, however, the number of interacting factors, including terroir and vine cultivars means that of the small amount of research undertaken, apparently contradictory results are common, so the impacts need to be assessed on individual vineyards.

There are also potential problems with non-biological mulches. Where there is vigorous earth worm activity, smaller particles, can be incorporated into soil quite quickly, and even large stones can be buried over a decade or so, as Charles Darwin’s earthworm experiments demonstrated (Darwin, 1881). Also, if these materials were brought into the vineyard, their dissemination through the soil may prove to be a problem when the vineyard needs to be replanted or is disestablished. In addition, alkaline rocks such as limestone, chalk and even marble can release sufficient calcium ions to cause a significant increase in pH, to the point it impacts vine performance, with it being difficult to reduce excessively high pH. Other rocks may also leach chemicals that negatively impact soil chemistry over time.

5.3.2. Biological particulate mulches

Biological particulate mulches cover a very wide range of materials, such as compost, tree bark, wood chips, pasture and cover crop mowings, sea shells, bone, grape marc, animal manure, paper, etc.

Their primary attribute, and the obvious converse of non-biological mulches is that they decompose, even shells and bones decompose over time, especially in biologically active soils.

Apart from the calcium based materials such as shells and bone, the decomposition time is mainly determined by the particle size and its carbon to nitrogen ratio. The larger the pieces and the higher the percentage of carbon (a high C:N ratio) the longer the material will last. However, even large pieces of tree bark may only last 3-5 years before being decomposed.

5.3.2.1. Effects on soil nutrients and pH

The key side effect of biological mulches is that when they decompose they add nutrients to the soil, and as they are typically applied in substantial amounts, e.g. 5 - 10 cm deep under the vines, this can equate to 100 - 500 tonnes/ha depending on the material. This can add a significant amount of nutrients such as potassium, phosphorus and calcium directly to the vine root zone which may bring nutrient levels above optimum, even for apparently woody materials such as tree bark, that is incorrectly considered to contain no significant amounts of nutrients. Calcium based materials, such as shells, are going to raise soil pH, the same as calcium rocks discussed above. Other materials can also raise pH, with compost being a prime example. Continual use of compost over many years can result in excessively high pH, along with excessive P and K levels (Prasad, 2009a, 2009b). Therefore the nutrient inputs and pH effects of mulches must be included in nutrient budgets and used in conjunction with soil tests to ensure vines are not over fertilised and pH is in the optimum range.

5.3.2.2. Use for weed management

The weed suppressive effect of mulch (excluding allelopathy, see below) is due to the mulch 'moving' the soil surface to a greater depth. To explain, most annual weed seeds are so small they can only emerge from the top two to five cm of soil, and the majority only emerge from the top 2 cm, as trying to emerge from deeper is suicidal. Therefore, weed seeds have a number of mechanisms that tell them how deep they are in the soil profile, such as monitoring oxygen levels, temperature and diurnal temperature range, presence/absence of sunlight, nitrate levels, and so on. By adding mulch to the soil, what was the soil surface is now several centimetres 'lower' so all the above soil factors are indicating to the seed that it is deeper in the soil than it actually is, so it avoids germinating.

To be effective for weed management mulches therefore need to be sufficiently thick. The thickness required is partly determined by the particle size, the larger the particles, and therefore the bigger the gaps / holes between them, the deeper the mulch required. Small particulate mulches, e.g. sawdust and compost, need to be at least 5 cm deep, while larger sizes, e.g. bark, wood chip, need to be at least 10 cm deep. The mulch also needs to be topped up on a regular basis to maintain the minimum depth.

The timing of mulch application is also important. Most annual weeds are summer annuals that germinate in spring. To be effective, mulch needs to be in place before the spring germination flush occurs, and also still in place for the autumn germination flush of winter annuals. If the mulch is applied after the weed seeds start to germinate, they may well grow up through the mulch.

While mulches can be really effective at suppressing annual weed seed germination, generally they have limited effect on established weeds, as these will normally have sufficient reserves to grow up through the mulch. Generally only sheet mulches, or very large depths of particulate mulch (e.g. >20 cm) are required to kill existing weeds. Also, mulch is an ideal material for creeping perennials, e.g. white clover, twitch / couch grass, to grow through as it is often rich in nutrients and the competition from annual weeds has been removed, so if such species exist in the mid-row, they are highly likely to quickly invade the undervine if mulch is applied. Generally such species are also highly resistant to thermal treatments - see section 6.4.

One exception to the above issues of mulch depth and creeping perennials, is paper mache mulch. Due to way that paper mache sets hard, it is more like a sheet mulch than a particulate mulch so quite thin depths, e.g. 1 - 2 cm are able to completely prevent weed seed emergence, and it can also kill existing weeds, and inhibit creeping perennials. It can also retain its effectiveness for 2-3 years. However, suitable sources of clean paper are limited, especially ones that meets organic standards. It is therefore considered unlikely that paper mache will be practical for applying to the whole undervine area on an ongoing basis, however, it may be a viable option for use around newly planted vines.

5.3.2.3. Allelopathic effects of biological mulches

A possible negative side effect of biological mulches is an allelopathic effect on the vines, mainly from allelochemicals from the mulch inhibiting vine roots. While no evidence has been found for this effect in the literature, all mulch parent materials should be checked to see if they are known to be allelopathic (e.g. walnut prunings) and if so they should be tested for their effects on the vines over several years.

5.3.2.4. Sourcing biological mulches

A key limitation with biological mulches is sourcing the material. A Marlborough District Council report on mulch in vineyards (Agnew *et al.*, 2002) estimated that when the vineyard is the only source of its own mulch, i.e. vine prunings and returned grape marc, then only about one-eighth of the vineyard could be mulched each year. As these materials are likely to last only two to three years before becoming ineffective, then external sources of mulch will be required. However, two key issues exist for such external sources:

- They are bulky so transport costs can exceed the material cost over pretty small distances, e.g. 50 km, so a local source of material is likely to be required for the economics to stack up;
- Over the last couple of decades, there have been many sources of mulches appear, often as the ‘waste’ product of another process (e.g. bark chips), so the mulch is often free to start with. However, it is not long before market forces kick in and the waste stream starts to become a lucrative secondary income as demand increases, to the point that higher value uses, e.g. biofuels, makes the material uneconomic as a mulch. Therefore, securing a mulch supply that is economic and will stay on-stream for decades can be challenging.

The main exception to sourcing sufficient biological mulches is to use the mid-row vegetation as the source. If vigorous species are planted, and kept well fertilised and watered, then a considerable amount of biomass can be produced, e.g., 15 tonnes / ha / year (continual ha). The biomass is also produced directly next to where it is required, i.e., the undervine, so it is easy to transfer it with purposed designed mowers. As it is fresh green plant foliage it can contain valuable amounts of nitrogen, thus supplying N to the vines (see also section 7.3). As it decomposes it often forms an interlinked mat, somewhat like paper mache, which weeds find it hard to penetrate.

5.3.3. Pest and disease interactions

One of the main concerns about using biological mulches made from vineyard sourced material, i.e. prunings and marc is that they will exacerbate fungal diseases. However, where scientific trials have been conducted, it has shown than undervine mulch both vineyard sourced and other materials, as well as cover crops had no effect on, or reduced, botrytis levels in the following crops (e.g., (Anon, 2006)). The indications are that the increased rate of decomposition of shredded prunings used as mulch and those prunings left on the ground were responsible for this effect.

5.4. Mowing

Mowing, along with cultivation (tillage) of the undervine area can be a management tool in and of itself as well as being a means of managing other undervine systems such as cover crops. Mowing can also be viewed as a less 'intensive' alternative to cultivation, though, in some key aspects it is fundamentally different.

The basics of mowing the undervine are the same as the use of mowing for weed or vegetation management in other settings, both agricultural, and amenity. Relating back to the underpinning biology discussed in section 4.4.4, mowing is rapidly lethal to annual and perennial plants that have their buds above ground, while those with their buds at or in the soil are highly tolerant of mowing and so survive. This means that if mowing is regularly applied to ground dominated by annual weeds, the selective mode of action of mowing will automatically push the weed / non-crop plant flora towards pasture species, especially grasses. Contrary to common-sense, eliminating large upright annual weeds and replacing them with mown grasses and pasture species may not reduce competition with the vines, because annual weeds are typically dicots with tap root systems that explore the bulk of the soil so potentially compete less with the vine feeder roots than grasses which have shallow, highly competitive, fibrous root systems. Mowing low and often to keep the grass short may also not reduce competition but may actually increase it because the tightly mown grass is trying hard to regrown its lost leaves so may be trying to extract more nutrients and water from the soil than longer grass that has stopped growing. However, no research has been found comparing mown with unmown grass, so, currently the effect is unknown. Therefore, above ground biomass, especially measured by height, is not necessarily a good indicator of below-ground competition.

Machinery for undervine mowing, cultivation and thermal weeding are detailed in section 6.

5.5. Cultivation

Where mowing does not achieve the desired reduction in competition with the vines, cultivation is the next, and more aggressive, option. However, among the different cultivation machines, there is considerable variation in how aggressive they are, with some weeding / cultivating only 2-3 cm deep with minimum soil disturbance while others will cultivate 5-10 cm deep, using powered tools, with large amounts of soil mixing.

5.5.1. Cultivation and the weed seed rain

And as noted above and section 4.4.4, cultivation will cause a shift in the weed species towards annual cropping type weeds due to the disturbed soil and elimination of existing vegetation. As discussed in various sections of 4.4, the key to successful annual weed management is preventing weed seed rain (setting viable seeds, and their return to the soil), so while it may not be necessary to control annual weeds in autumn as competition with the vines is limited, it is essential to control them to prevent weed seed rain. If this is not done the annual weed population will (not may) become so large that they will become impossible to control. Further, most annuals can and do produce viable seed within a week of flowering, therefore when such weeds start flowering they should be controlled immediately.

5.5.2. Impacts on feeder roots

Also as discussed in section 4.3.1 (Roots) cultivation may have a significant impact on vine feeder roots. Where cultivation is used regularly, it is probable that the vine feeder roots will 'move' below cultivation depth (i.e., they will no longer grow in the disturbed surface layers), so there may be less long term impact on the vines. However, where cultivation is used intermittently, e.g. alternating with a cover crop, or especially a fertile biological mulch such as compost, the vine feeder roots are likely to move towards the soil surface, and then be significantly damaged when cultivation occurs. It is unclear from the literature how significant this effect is and how quickly vines recover, but it is likely to be influenced by the rootstock, possibly also the scion, and also soil structure and fertility.

In the absence of good research data, it may be prudent to start cultivation as shallow as possible progressively increase the depth of cultivations. It probably also prudent to test cultivation on small areas of the vineyard to start with, just in case there are any significant negative effects.

5.5.3. Impacts on soil

One of the key concerns about the use of cultivation for undervine management is negative impacts on soil. However, the actual situation in vineyards may not be as black and white as some of the views held.

5.5.3.1. What is the biggest cause of soil harm: undervine cultivation or mid-row compaction?

First, cultivation is clearly harmful for soils / reduces soil health. However, most of the research data on this topic comes from annual cropping systems where the entire A horizon is cultivated, and cultivation with considerable intensity, e.g., ploughed on an annual basis, with multiple passes with machinery such as a rotary hoe. In comparison, in a vineyard, only the undervine is cultivated, rarely deeper than 10 cm (often much less), but with potentially multiple passes a season. For a arable field cultivated to 30 cm deep 3,000 m^3 of soil is disturbed per hectare, while in a vineyard with 2 m centers, 0.75 m wide undervine cultivated 10 cm deep, only 375 m^3 of soil is disturbed, i.e. only 13% of the soil disturbed in the arable system. The amount of damage caused to a soil is dependent on the volume, intensity and frequency of cultivation. Therefore by this measures, the lower soil volume, moderate intensity but higher frequency, the impact on the total soil within a vineyard from undervine cultivation is much less than in an arable system.

However, at the same row spacing of 2 m, there are 50 mid-rows per ha (100 m x 100 m square) with a total length of 5 km. Each has two, approx. 40 cm wide tractor wheelings, with a compact zone under them 75 cm deep (it is often deeper and extends much wider than the surface tracks) which represents 3,000 m^3 of soil negatively effected by compaction compared with the 375 m^3 of cultivated undervine soil. It can also be argued that the compaction has a worse effect on the soil structure than the undervine cultivation. Therefore, while undervine cultivation may be a highly visible form of soil damage, mid-row compaction also causes considerable harm and reduction of soil health.

The caveat regarding the above argument based on the volume of undervine soil directly impacted by cultivation, is that the cultivation eliminates undervine plants (weeds and non-crop plants) which has a much wider negative impact on undervine soil health, to depth, far beyond the direct damage from the weeding tools themselves. The overall message is therefore that the highly visible impact of undervine cultivation for weed control, is the tip of the iceberg, but, the elephant in the soil health room is compaction from machinery in the mid-row.

5.5.3.2. Impacts on soil biology including mycorrhizal fungi

Concerns are also raised about the impacts of undervine cultivation on soil biology, and especially mycorrhizal fungi. The increasing view among soil scientists is that cultivation is harmful to soil not only because of the direct physical damage, but, more importantly, due to the elimination of living plant covering the soil (described as 'soil armour') as those plants are no longer feeding the energy captured from the sun, in the form of carbon based compounds, into the soil around their roots.

There is also the loss of above-ground residues, i.e. the reduction in living plants has as large, if not larger, impact on soil health as does the direct effects of cultivation and toxicity of herbicides (e.g., see section 10.5). This is why continual herbicide strips cause a major reduction in soil health in the complete absence of cultivation (Curtin *et al.*, 2015).

It is possible to partly mitigate this damage by supplying plant residues to the cultivated undervine area, ideally in the form of undecomposed residues such as mowings from the mid-row, or decomposed plant matter, e.g., compost. However, the negative physical effects of cultivation will still remain, so, cultivation will always be more harmful than mowing, which will still not be as good as a permanant actively growing vegetation cover.

In relation to mycorrhizal fungi, and all filamentous soil fungi, it is completely clear that cultivation kills them. However, the damage is limited to the soil that is directly cultivated so the fungi can persist in the undisturbed soil. Therefore, based on the discussion in section 5.5.3.1 directly above, that a very limited volume of soil is cultivated in a vineyard, it is probably that the total impact on mycorrhizal fungi is limited, and also the comments above regarding where cultivation is used regularly the vines may adjust their feeder root positions below the cultivation zone, and if so, then the mycorrhizal fungi will follow the vine roots. However, the research in this area is very limited, so verification is required.

5.5.4. Effects of cultivation on soil nitrogen and other nutrients

One effect of cultivation on soils with good levels of organic matter, particularly less recalcitrant forms, is increased mineralisation of the organic matter and therefore release of nutrients, especially nitrogen (see section 4.2). Cultivation can therefore release an agronomically significant amount of N, e.g., 10 to 30 kg/ha. However, the amount released will vary considerably, as it depends on the amount of readily mineralisable organic matter in the soil, general soil and atmospheric temperatures, and also if the vine roots are capable of taking it up. Regular cultivation will reduce the effect, while infrequent cultivation will build up a store of N which can then be released.

5.5.5. Changes to vineyard infrastructure

At a practical level, introducing mowing, cultivation and/or thermal weeding to the undervine may require some infrastructure modifications.

Irrigation pipes / driplines may need to be lifted above the height of the machinery - probably to the bottom wire. Moving dripper locations away from vine stems to mid way between vine to reduce weed growth around stems may also be beneficial.

Particularly where machines with less sensitive guidance systems are used (section 6.1.4) protecting young vines and other structures, e.g., irrigation valves etc., with small posts, poles, etc., that can activate the guidance mechanism, will be essential.

5.5.6. Stones - moving back into the row

Cultivators, depending on the design, may well throw stones out of the undervine area into the mid-row where they can be a hazard. Some cultivators therefore have attachments that push such stones back into the undervine area. These are mostly based around a flat faced steel beam angled at about 45° to the direction of travel. Such devices can be constructed as a stand-alone three point linkage implement .

6. Organic undervine weeding techniques

Globally and in New Zealand the range of undervine weeding machinery continues to expand, with both imported and locally designed and made machinery. Choice can sometimes be confusing, so the following section aims to highlight the key design and usability issues that should be considered. Inclusion here does not mean that the particular machine is currently available within NZ.

There are three general approaches / types of undervine weeder:

- Mowers
- Cultivators / tillers
- Thermal - flame and steam

Mowing and cultivation are by far the most common approach, while thermal is used rarely and typically only where mowing and cultivation are not achieving the desired outcomes.

6.1. General considerations for mowing and cultivation

6.1.1. Tractor mounting

Both undervine mowing and cultivation are specialist tasks, and therefore require specialist equipment. This then also means that standard, rear, three point linkage attachment is only one option, with both front (fixed and three point linkage) and mid-mounting also being possible. Mid mounted equipment is generally not quick or simple to attach or remove so should be considered permanant, at least for the weeding season, or unless toolcarrier tractors are used. Likewise some front mounted equipment has to be bolted on, so should be considered a fixture for the weeding season, while front three point linkage machinery is by definition straightforward(ish) to remove.

6.1.1.1. Steering accuracy

The three mounting positions also have implications for accuracy: due to the steering dynamics of front wheel steer tractors, mid mounting gives the most accurate placement, followed by front and then rear mounting. However, as most machines have some form of sensor system to guide the weeding head, this is not as critical as other agricultural areas, e.g., interrow hoeing crops. Front mounting has the additional issue that the motion of the weeding head can make steering more difficult due to the sideways force of the weeder. On the plus side, having the weeder on the front or mid-mounted makes visual observation easy so the weeding operation is more easily monitored.

6.1.1.2. Depth wheels

Depth control wheels should also be considered, because for many operations, accurate ground following is required, that is beyond what can be achieved via three point linkage height control. This is especially true of vineyards with uneven ground and/or slopes.

6.1.2. One row or two?

Typically both sides of the vine row need to be mown or weeded as the tools are unable to cover the entire undervine from one side. As with other vine row operations, treating two vine rows at a time will therefore halve operation time, however, capital cost is higher for two rather than one row machines. For cultivators, especially those that operate at depth or move significant amounts of soil, the draft forces can be quite large and therefore beyond the ability of smaller tractors. At the same time single sided machines with high draft also produce a skewing effect on the tractor complicating steering.

6.1.3. Combining undervine and mid-row equipment

Often the mid-row requires a management operation, e.g., mowing, at the same time as undervine mowing or cultivation is required. Systems that allow for both sets of equipment, or using machines that perform both tasks, can save a considerable amount of tractor time. The downside of this is considerable power may be required, so, higher horse power tractors may be needed, with multiple tools, more hydraulic connections may be required, and with multiple operations running at once, superior tractor operator skill and attention are needed.

6.1.4. Weeding tool guidance

As nearly all cultivators aim to cultivate between vine stems, a mechanism is required to move the weeding tool around vine stems, posts and other objects on the ground (e.g., irrigation taps). The first two approaches are an automated system or manually operated. Automated systems tend to cost more, due to the extra equipment needed, however, the manual systems require considerably more attention and skill from the operator, and mistakes are likely to mean lost vines, and/or post or equipment damage. Considering the large number of vines and posts in a vineyard and the number of passes each year, even a small number of operator errors can add up to significant vine losses and equipment damage.

6.1.4.1. Automated systems

Automated guidance systems are based on three broad approaches with pros and cons.

- Mechanical
- Hydraulic
- Electric-hydraulic

Mechanical is typically based on a 'nudge bar' that engages the vine, post or other obstacle which is physically / mechanically contacted to the weeding tool but slightly ahead of it, with both bar and tool sprung loaded, such when the nudge bar hits an obstacle, the spring loaded tool swings around the obstacle.

Hydraulic systems, are based on a 'sensor bar/wand' connected to a hydraulic valve such that when the wand touches an obstacle, it opens the valve and the weeding tool is moved around the obstacle by a hydraulic ram.

Electric-hydraulic systems also use a sensor wand, but these are attached to an electrical sensor, that then actuates a hydraulic system for moving the weeding tool around the obstacle.

There are a number of pros and cons for each system (Table 2). These are based around:

- The 'resistance' or force exerted by the sensor system, some require a large resistance, so they wont be activated by young vines, or other small obstacles, while at the other extreme some are very sensitive e.g., touching a plastic vine guard would activate them.
- Speed, i.e., how fast the weeding tool can move in and out of the row, this governs how fast the tractor can operate, though weeding tool type also determines maximum speed.
- Proportional control, i.e., the weeding tool follows the shape of the obstacle, vs. a simple open & shut system.
- Adjustability, i.e., can the sensitivity be changed (e.g., so it is not activated by large weeds) and also can the size of the 'safety zone' that is left unweeded be adjusted.

Table 2. The pros and cons for the three main tool guidance systems.

Approach	Resistance	Speed	Proportional	Adjustable
Mechanical	Largest	Slowest, as the force exerted increases with speed	yes	Possible
Hydraulic	Low	Med to high, depending on hydraulics	yes (flow valves)	Possible
Electric-hydraulic	Lowest	Highest - higher capacity valves can be used	yes (electronically)	Yes

6.2. Mowing

Undervine mower designs are nearly all based on a vertical axis, horizontal blade designs (Figure 2) as opposed to sickle-bar or horizontal axis flails, for example, as this design is best suited to undervine mowing.

Figure 2. Examples of vertical axis, horizontal blade system in undervine mowers.

The key design issues to consider are:

- The ability of the mower to cope with both thick tall vegetation as well as mowing close to the ground.
- Ability to follow uneven ground.
- Able to cope with hazards such as stones.

6.3. Cultivation

Compared with the single optimal design solution for mowers, the range of options for undervine cultivation is very diverse, from simple draft tools, to complex powered tools. All of these are essentially miniature versions of standard cultivation / tillage machinery.

6.3.1. Draft tools

The two main approaches for draft tools are:

- Horizontal ‘knife’ blades to cut weeds off at soil level (Figure 3);
- Vertical, tines, disks, chisels etc to cut, lift and mix soil and weeds, from two to ten centimetres, or more, deep (Figure 3).

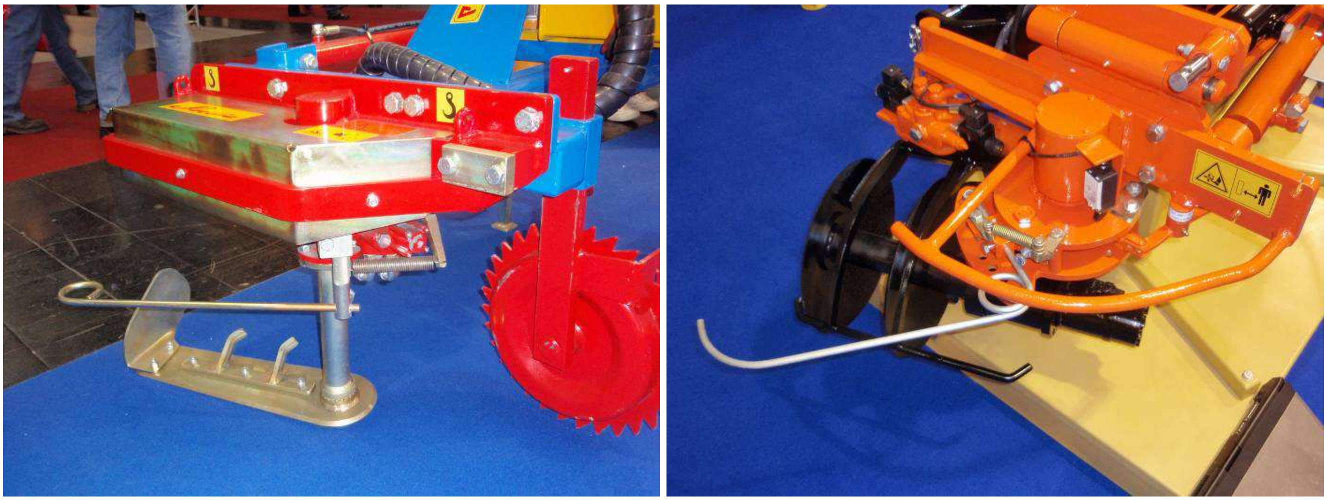

Figure 3. Draft weeding tools: Horizontal ‘knife’ blade (left) disks (right).

Horizontal blades are based on the same approach as field-vegetable and arable crop interrow hoes. They aim to separate the roots and shoots of plants (cutting them at the hypocotyl) which is the most effective means to kill most annual weeds. If correctly set, and with flat soil surface, they can cut only a centimetre or so deep, with the minimum amount of soil mixing, so potentially have the minimum impact on soil and vine roots. They can also be set deeper, but, as the weeds will be cut not at the hypocotyl, but through the roots (root pruning), weed mortality may well decrease.

Vertical tools, by their nature can’t cut horizontally through the weeds hypocotyl, so they rely more on ripping the whole weed out and cutting, mixing and burying the weeds in the soil to kill them. They also have to mix and move more soil than horizontal blades to kill the weeds, which may be both good and bad.

Some vine systems will want the minimum amount of soil moved, while others will benefit from, for example, hilling soil up around the vines in spring and then pulling that back down later in the season. It is not therefore possible to give hard and fast rules as to which machines and cultivation approaches are best, as this needs to be tailored to each vineyard.

6.3.2. Powered tools

There are a wide range of powered cultivators, as many, if not more as there are powered field cultivators, see Figures 4 5 and 6. NB not all of these designs may currently be available in NZ, but they illustrate the diversity of approaches in use globally.

Figure 4. Powered undervine cultivators: left, rotary hoe / rotovator type, right, vertical power harrow type.

Figure 5. Powered undervine cultivators: left, vertical spring rods, right, vertical axis wire brush.

Figure 6. Powered undervine cultivators: left, vertical axis vertical rotating disks (‘cyclone’), right, vertical axis horizontal rotating disk.

There is a lot of detail to be taken into consideration for any powered undervine weeder. The key issues are:

- Powered weeders, buy their very nature, are likely to cause significantly more disruption to soil quality than draft tools, especially in terms of damage to soil structure.
- The amount of tractor power required, and the means of transferring that power to the weeding tool - either mechanical from the PTO or hydraulic.
- While draft is typically much lower for powered tools, total tractor power requirements may be much higher, especially for hydraulic systems, so more powerful tractors may be required.
- Aggressiveness vs. power required and soil damage. Typically more aggressive tools, e.g., rotary hoe (Figure 4) will kill more weeds than less aggressive tools, e.g., the ‘cyclone’ in Figure 6, but they require more power, and also cultivate more soil, which will cause increased damage to soil.
- Tools vary in their ability to deal with dry and wet soils and also stones, some will be effective over a wide range of moisture and stone contents, while others will have their efficacy reduced.
- The cost of replacing wearing parts, especially if they are proprietary, can be considerable.

6.3.3. Scarifiers - a half way house

Recently a few machinery manufacturers have developed a half-way house between mowing and cultivation in the form of scarification. The concept is akin to scarifiers used in lawn / turf systems to remove thatch. The scarifiers developed for the undervine are somewhat more aggressive in that they aim to destroy the crown of pasture plants, i.e. the location of their buds, so that it either kills them or sets them back considerably, thereby, in theory, causing a commensurate reduction in root competition, but with much less soil disturbance. The aim is to gain a similar level of undervine weed control as cultivation, but with fewer of its downsides, such as higher fuel use and slower forward speeds. However, while the theory is quite reasonable, due to the novelty of the system, there is limited vineyard experience and no scientific studies, so more research and vineyard trials are clearly needed before more firm conclusions can be drawn.

6.3.4. Weather, soil moisture and cultivation

The weather and soil moisture (dry or wet) have a major influence on the effectiveness of cultivation for weed control - in any farming system, not just viticulture. Hot dry weather and hot dry soils are optimal for weed death, as any weeds not killed outright by the weeding tool, will then desiccate before they can regrow. Conversely, weeding in rain and wet soils can result in very high weed survival rates, such that it may well be a complete waste of time weeding in such conditions.

Complicating matters is that dry soil is often hard, and therefore difficult to cultivate which results in lower weed kills. Also in many of New Zealand fine silt soils, dust can also be a significant issue, especially for powered cultivators. Successful organic arable and vegetable farmers therefore constantly keep one eye on the weather forecast and the other on the weeds and soil conditions aiming to pick times to weed when the weather will be hot and windy but soil conditions still moist, so they get the best result.

6.4. Thermal weeding

Thermal weeding uses heat to kill plant foliage, either in the form of flames, steam or hot water. There are a considerable number of misconceptions about thermal treatment, so an overview of the technology is presented below.

6.4.1. Mythbusting thermal weeding

There are a wide range of potential thermal weeding technologies, including flame, infrared, steam, hot water, water foam, UV light, lasers, microwaves, and focused sunlight. However, many of these are economically and/or practically unviable in an agricultural environment, including, lasers, microwaves and UV light. Other technologies have niche applications, where a number of factors have to be correct to make them viable, these include, infrared and focused sunlight. The remainder: flame, steam, hot water and hot water foam have potential in a vineyard setting.

The aim of hot water foam is to increase the dwell time of the heat on the target plants, however, the limited research that has been done indicates no benefit, and a thermodynamic analysis indicates that any possible advantage will be small, and therefore may not offset the increased cost and complexity. Foam can only be used with hot water not true steam, as the rapid increase and decrease in steam gas volume destroys the foam, and hot water is considerably less effective at heat transfer than steam. Foam also requires the ongoing purchase of the foaming agent, and there is evidence of negative impacts on the soil system from the foam (Cederlund & Börjesson, 2016). Foam is therefore currently considered unproven to have any advantages over hot water or steam.

Of the three remaining approaches there are a number of pros and cons for all of them, which are outlined in Table 3.

Table 3. Pros and cons of steam, flame and hot water for thermal weed control in a vineyard

	Steam	Flame	Hot water
Mechanical complexity / cost	Med to high	Low	Med to high
Heat transfer effectiveness / fuel efficiency	Best	Worst	Medium
Water consumption	Medium	None	Highest > 6 times
Fire risk	Very low, to none	Extremely high	None
Risk to plastic, e.g. irrigation	Low	Extremely high	Low
Fuel type	Diesel or LPG	LPG	Diesel or LPG

6.4.1.1. Mechanical complexity and cost

Expanding on Table 3 the key difference between the three techniques in terms of the machinery is that flamers are the simplest - just LPG bottles, pipe work, regulators and the burners, while steam and hot water systems are similarly complex requiring diesel or LPG burners which are complex items by themselves which include a fuel pump and fan, a boiler - pressurised in the case of steam, water pumps, power, either electrical or mechanic to drive all the components and fuel and water tanks. Steam and hot water weeders are therefore considerably more complex and therefore more expensive.

6.4.1.2. Heat transfer effectiveness / fuel efficiency

There is considerable confusion in the relative effectiveness of different flame, steam and hot water weeders. For all three techniques the conversion of chemical energy into heat (thermal energy) is close to 100% efficient. What therefore separates the effectiveness of the machines is the efficiency by which the heat that is created is transferred to the target plants to cause plant death. If you have a 100 kw steam, hot water and flame weeder and each of them could be designed so all of the heat was used just to kill the plants and go nowhere else, all three machines would be equally effective. However, the effectiveness of heat transfer varies considerably, and the effectiveness also depends on the target weeds and also the system (e.g. vineyard vs. vegetables) they are used in which constrains the machinery designs that are possible.

The key issue for flame is that it uses air to transfer the heat, but, air is a great insulator / a very poor conductor of heat. Hot air also rises quickly so it needs physical containment to keep it close to the target plants long enough. It is difficult to design an application system for a vineyard (or any perennial crop) that can keep the high volumes of hot air produced by flame weeders close to the weeds, but not on the crop, for long enough for effective heat transfer.

In comparison, steam and water are much more effective than air as means of transferring heat due to their high energy density and the rate at which a significant weight of water and steam can be applied. It takes six times as much energy to turn liquid water at 100°C into true steam at 100°C as it does get liquid water from 0°C to 100°C in the first place. To illustrate, if a pot of liquid water on a stove at 0°C takes 10 minutes to come to a boil (100°C) then it will take another 1 hour (60 mins) to boil dry. When the steam condenses back to water, all that extra energy is released into the target - in our case the weeds. Its unusually high "latent heat of condensation" gives steam the clear upper hand.

In summary, steam is the most effective means of transferring heat into undervine plants in a vineyard situation, and as heat transfer efficiency determines fuel efficiency, it means steam is the most fuel efficient and is therefore the preferred option.

6.4.1.3. Water consumption

Hot water, lacks the benefit of the large latent heat of condensation, which means from the physics alone it requires at least six times as much water to transfer the same amount of heat as steam, and due to other issues around temperature differences and the amount of non-target material that is heated, especially soil, at a practical level considerably more than six times the amount of water is needed for hot water compared with steam weeding.

As a steam weeder can use hundreds of litres of water a vineyard hectare, hot water weeders will be requiring thousands of litres, which in most cases makes them impractical. The only advantage of hot water over steam is that in a limited number of studies hot water was slightly more effective at killing rosette forming weeds, as the hot water was more effective at reaching the buds of such species.

Flame weeders don't use water.

6.4.1.4. Fire risk and risk to plastic, e.g. irrigation

Flame weeders are a clear and obvious fire risk with their powerful, high temperature (max of 1,500°C) open flame burners. They are also a significant risk to plastic items in the treatment zone, such as sheet mulches, and irrigation pipes and fittings. Flamers are also quite capable of igniting biological mulches, such as tree bark, wood chips and even dry compost.

Steam and hot water are a very low or even negative fire risk because the flame is contained within the boiler, isolating it from combustible materials, while the presence of water is inhibitory to materials igniting even though they are heated up.

6.4.1.5. Fuel type

Flame weeders mostly run on LPG / pure propane, and with the high consumption rates several hundred kg of fuel needs to be carried on the weeder.

Steam and hot water weeders are normally powered by diesel, though they can also use LPG with duel-fuel options available.

It is possible to use renewable fuels in all machines. Biogas, from biodigesters is methane, while LPG is a butane-propane mix, so methane can be substituted for LPG with minor adjustments. Likewise, bio-diesel, renewable diesel and plain vegetable oil (even filtered recycled cooking oil) can be substituted for diesel in steam and hot water weeders, with minor component changes.

6.4.2. Thermal weeding - machinery conclusions

Based on the above, particularly the issues of heat transfer efficiencies and fire risk, plus water consumption rates, steam weeders are considered the best option for New Zealand vineyards. It is noted that the number of vineyard steam weeder suppliers in New Zealand is limited.

6.4.3. What thermal weeders can and cannot achieve

In addition to misinformation around the types of thermal weeders and their pros and cons, there are similar myths and misunderstandings around what thermal weeding can achieve. Put simply, thermal weeding is equivalent to a contact herbicide, in that it can only kill plant foliage that it contacts. Good 'coverage' is therefore essential to ensure maximum foliage death. In addition, it is not the weeds leaves that are the primary target, as outlined in section 4.4.4, it is the above-ground meristems, i.e. the weeds buds that have to be killed to achieve plant death. In this respect, thermal weeding has a similar effect to mowing (see section 5.4) in that it is most effective against upright plant species, while in comparison, many pasture species, especially grasses are highly tolerant, so where thermal weeding is used regularly the weed / undervine flora will shift to pasture species as it does with regular mowing.

Why then use thermal weeding instead of mowing? With sufficiently frequent use, thermal weeding can kill established plants, so it is possible to achieve a plant free undervine with thermal weeding, and, thermal weeding can kill vegetation directly around the base of vine trunks and posts, so only thermal weeders can achieve a plant free undervine without soil disturbance (i.e. the same as herbicides). Thermal weeders can also be used on stony soils, that would be impossible to mow or cultivate, or at least that would be very hard on machinery. Steam and hot water weeders can also be used on biological mulches to manage weeds that grow up though them (flame weeders are a fire risk, see above). Where one or more of these situations exist, then thermal weeding has an advantage.

6.4.4. Effects on soil biology from thermal weeding

Concerns are often raised about the effects of thermal weeders on soil biology. The direct affect of thermal treatment on soil and soil biology is effectively zero, as there is negligible soil heating, e.g. a few tens of degrees (i.e. warm) for a few tens of seconds. This is because soil requires many magnitudes more energy to heat it, than air and weeds, so there is simply insufficient heat generated by thermal weeders to do any harm. In comparison, bright sunlight, can raise the soil surface temperature tens of degrees hotter than a thermal weeder can, and keep it at that temperature for hours, not tens of seconds.

However, thermal weeding does cause indirect soil damage though the elimination of growing plants (see section 5.5.3.2).

6.4.5. Electrothermal weeders

Electrothermal weeders work by using high voltage (500 to 10,000 V) to boil weeds from the inside thus killing them (Merfield, 2016). There are two key advantages of electrothermal. The first is that as the electricity travels down the plant stem, through the hypocotyl and into the root system, it has a systemic kill effect, unlike other thermal weeders which are only a contact kill. It can therefore kill many species of weeds in one application, that would take multiple application of flame, steam or hot water. It is also much more energy efficient, as, only the plant is heated, not the environment, and if there are no plants no energy is being used, unlike flame, steam and hot water which continually produce heat regardless if weeds are present or not.

The technology was first patented at the end of the 1800s but never took off. There was a resurgence in the 1980s, which again petered out. With rapidly increasing evolved resistance, and prohibition of herbicides in places such as the European Union there is a renewed interest in electrothermal and two companies currently produce electrothermal weeders Zasso[5] and Rootwave[6]. Electrothermal weeders are considered to have significant potential for undervine weed control, however, globally there are currently no commercially available machines for viticulture or perennial crops, though it is hopes that machines will be developed over the coming years.

6.5. Organic approved herbicides

There are a small number of certified organic herbicides. Most are plant derived fatty acids, which kill plants via a physical-chemical mechanism, e.g., they dissolve cell walls, compared with the biological-chemical (biochemical) approach of most non-organic herbicides which disrupt the biochemistry of plants. Fatty acids are purely contact herbicides and generally work only on green not lignified tissue. They also need higher temperatures and bright sunlight to work effectively. In cold overcast conditions they may not work at all, although there are examples where they have

[5] zasso.eu
[6] rootwave.com

been applied in cool overcast conditions to no effect, but, several days later when hot sunny weather comes along, they then start working! To reiterate, they will only kill plant tissue they contact on so unsprayed parts, e.g., lower leaves shaded by upper leaves will be unharmed, and as they are contact, not systemic, they can't kill the root system.

The one alternative to fatty acids is acetic acid, i.e., vinegar. However, the 4% vinegar available in food shops is wholly unsuitable: the concentration needs to be around 20% to burn most weed types, at which concentration it is highly caustic and therefore dangerous, in the same way sulphuric acid is dangerous. Great care, and the use of appropriate safety equipment is required. It is also vary harsh on spraying equipment and will corrode many metals. Like the fatty acids it is only a contact, not systemic herbicide. One potential advantage over the fatty acids, is, because of its lower viscosity and stickiness, it will run down into the growing points of rosette forming weeds, killing them.

Generally the limitations of organic herbicides have resulted in low uptake by growers, with their use being restricted to specific situations where other techniques are proving inadequate.

7. The mid-row / interrow

Traditionally the mid-row has been something of a non-area in many vineyards - it is merely the gap between the vines required for machinery and personnel access. Less thought has therefore been given to its use and management with mown grass swards being a typical approach. However, the interrow has considerable potential to add to overall vineyard management, improve vine production and health, and help meet wider environmental and sustainability objectives. The key management approaches include:

- Growing cover-crops and green manures;
- Growing conservation biocontrol plants;
- Increasing biodiversity;
- Extra cash crops.

7.1. Mid-row cover crops

Most of the general and a range of detailed information on using cover crops has been covered in section 5.2 with additional theory in section 4.4. This section will therefore only cover issues specific to the mid-row.

7.2. Vine competition

While the undervine is the area where the largest amount of competition with vine roots occurs, in some vineyards vine roots, both surface feeder and deeper water gathering roots, can extend into the mid-row. In such situations growing cover crops, and other activities, such as cultivation including deep ripping / sub-soiling may have a considerable impact on the vines. The presence of roots therefore needs to be determined, by digging soil pits, at multiple points in the vineyard to look for vine roots. Soil type and structure are the main determinant if vine roots can grow into the mid-row, so where vineyards have different soil types, especially if they vary widely, each soil type should be checked. Where vine roots are present, then a precautionary approach is advisable, with a number of small areas trialled first, before using a cover crop or other change to the mid-row, before extending to the whole vineyard.

7.3. Mid-row green manures for nitrogen fixation

Despite there generally being far fewer vine feeder roots in the mid-row to take up fixed nitrogen, on balance, it may be the better place to fix nitrogen than the undervine, due to the competition with vine roots in the undervine area and the greater difficulty of managing cover crops under the vines.

The key to such a system is being able to transfer the N fixed in the mid-row into the undervine area. While there will be some natural transport of N through the soil system, both by diffusion and active movement by plant roots and mycorrhizae, this may be insufficient. The simple solution is to cut / mow the mid-row vegetation and move the cuttings to the undervine area. There are a range of mowers with side discharge systems built for this purpose.

7.3.1. Turning N supply on and off

An additional advantage to such as system in that N delivery to the undervine area can be turned on and off, by either moving cuttings to the undervine or leaving them in the mid-row. However, this cannot be as precise as soluble fertiliser (not permitted under organic standards), as the mulch has to decompose before the N is released. If the rate of release needs to be speeded up, then cultivating the mulch into the soil surface may speed up decomposition and N release, on the proviso that soil temperatures are high enough (see section 4.2.4).

The legumes in the mid-row will also continue to fix N until available soil N becomes high (see section 4.2.4) so even when mowings are not moved to the undervine, if the vines are able to access the N they may become over-vigorous, in which case the legumes may need to be removed. Conversely, for N deficient vineyards, removing the mowings and N from the mid-row means the legumes are forced to fix more N, which is then transported to the undervine, creating a ‘N factory’ within the vineyard.

The cut mid-row vegetation transferred under the vines can also suppress weeds i.e., it acts as a mulch (see section 5.3.2), if a continual thick layer (e.g., > 5 cm) can be achieved.

On the downside, a thick layer of mulch under the vines will insulate the ground and may well increase frost risk (see also section 5.2.10).

A key issue with this system is that it is not only N that is being transferred from mid-row to undervine, but the full range of plant nutrients. Where such systems are used over many years, it is essential to measure the soil nutrient status of mid-row and undervine separately and to make sure that nutrient levels under the vines don't become excessive, and to ensure than nutrient levels in the mid-row are sufficiently maintained.

7.3.2. Perennial species for the midrow

The typical green manure for these kinds of systems is a grass and white clover sward. This is because they survive regular mowing due to their protected growing points. In comparison, other perennial legumes such as red clover and lucerne with their vertical stems will die out under frequent mowing. Where these forms of legumes are used, mowing or grazing frequency needs to be considerably reduced and the plants allowed to gain their full height, which can be 30 to 50 cm to avoid them dying out. This may start to interfere with vineyard operations.

While grass does not fix nitrogen so could be considered of no value, it fill the ecological gaps left by the legumes, so helping to suppress weeds, and its fibrous root system is also very good for creating good soil structure.

A wide range of other plant species can also be used in the sward, such as herbs / forbs, e.g., chicory, plantain, etc., for a range of benefits such as biodiversity, better livestock nutrition when they are used in the vineyard, and greater depth of rooting.

7.4. Mid-row cover crops without N fixation

Where N fixation is not required, a wide range of cover crop options and purposes exist.

7.4.1. Excess vineyard nitrogen

Where there is excessive vineyard vigour due to N, there is potential to use mid-row cover crops to remove N, by harvesting and removing them. For the maximum N removal, the cover crops should be harvested green, as N content often falls as plants mature. Clearly non-N fixing species are required, and ideally species that produce a lot of biomass and use a lot of N, e.g., cereals such as triticale and Ryecorn. A caveat is that such an approach will also remove other nutrients as well, especially phosphorus and potassium, which will need to be replaced.

7.4.2. Conservation biocontrol

The mid-row is an easy location to plant conservation biocontrol plants (section 4.4.5.1) as the complexities of undervine interactions are avoided, and the biocontrol plants can be optimally managed according to their needs. This is not to say that biocontrol plants should not be grown undervine, as were the system works well, there may be a number of advantages that mid-row biocontrol plants cannot offer.

7.4.3. Biodiversity

On the same logic that plants in the mid-row have the least direct competition with the vines, the mid-row is also an easy place to grow plants to increase biodiversity. While planting things such as wildflower mixtures, may intuitively feel like it is providing great biodiversity, and they certainly can look spectacular, such approaches may not be the best approach for maximising the total amount and total diversity of species. Typically wildflower mixtures are wholly exotic and many of the flowers are not good nectar or pollen sources for smaller beneficial insects.

However, there is no one ‘magic’ biodiversity mixture - only horses for courses. Perhaps the best all rounder is a diverse mixed species pasture, while multiple grasses, legumes, and herbs / forbs. It is also important to allow the pasture to grow longer between mowings, as this will let some forbs and legumes flower, it will provide more places for insects, and increase carbon fixation.

However, if maximising a wide range of biodiversity is the aim, it is likely that a range of different plant systems will be required. To date there is limited research in this area.

7.5. Mid-row cash crops?

Globally, some winegrowers grow cash crops in the mid-row, e.g., cereals. While an interesting and attractive idea, there are a considerable number of practical issues that need be resolved, therefore detailed research and planning are required and systems should be tested on small areas to start with to test for unexpected results, before rolling out to the whole vineyard.

7.6. Mid-row cultivation

While less desirable from a sustainability and ecological standpoint, cultivation / tillage of the mid-row to eliminate all vegetation, as a management option should not be ignored. For example, cultivation of mid-row can release significant amounts of N and other nutrients, which may be accessed by the vines. However, the amount of this flush will decrease with each subsequent cultivations as the amount of easily decomposed organic matter, that was built up under the previous sward or cover crop, decreases .

Where the mid-row is being cultivated prior to sowing new plant species, the potential for an N flush to cause excess vine vigour needs to be considered.

8. Livestock

The use of livestock, particularly sheep, in vineyards for management of vineyard floor vegetation overwinter and also leaf plucking is growing in popularity in NZ. However, as a still relatively novel practice, there is still much to be learnt about optimal use of livestock so no guidelines are given here, however, there are a few issues that need to be considered, especially for certified organic production.

Ideally, especially in terms of certification, only organic stock, permanently kept on the organic vineyard would be used. However, the seasonal nature of grass growth and the extra work required often means this is impractical. The next best option is working with local organic stock farmers, to use their stock as and when required. Such arrangements can be highly beneficial, but, such opportunities may be limited (i.e., insufficient organic livestock producers close to organic vineyards) and pre-approval from both producers' certifiers should be obtained and detailed records should be kept of all stock movement, both between farm and vineyard and around the vineyard.

If organic stock are not available, it is possible to use non-organic (conventional) stock on organic properties, providing that certification rules are followed. Key among these are that stock may have to go through a quarantine period of 24 to 48 hours, in a designated quarantine area before being released onto the wider vineyard. Also, the stock must **not** be treated with any prohibited materials, e.g., drenches, while on the vineyard, otherwise the vineyard may loose certification, i.e., that the stock are not organic is not an issue, it is the use of a restricted or prohibited input on the stock while **on** the vineyard that is the certification issue. If animals need to be treated, they must be removed from the property, treated, and then go though the quarantine system again, before being returned to the vineyard.

As with all management practices that may have a certification impact, talk with your certifier first.

There are also issues around spray residues in stock meat, especially where stock are used for leaf plucking. While this is almost entirely focused around non-organic vineyards and mostly around sprays that are prohibited in organic production, there are also organic specific issues. Organic consumers typically expect lower agrichemical residues in organic produce, so any activity that may increase residue levels, may have market implications. In addition excess copper is toxic to sheep so its use should be avoided if sheep are used for plucking, and even where sheep are just grazing the vineyard floor, pasture may well be 'contaminated' by copper sprays used on the vine canopy. For more information see (Emms, 2010).

9. Conclusions

Humanity is facing an unprecedented number of global and local challenges, such as global heating, biodiversity loss / the 6th great extinction, loss of soil, excess P and N in waterways, etc., (Anon., 2015; Steffen *et al.*, 2015; Conijn *et al.*, 2018). At the same time many of the technologies that have created modern agriculture and horticulture, such as the pesticides are failing, e.g., through evolved resistance, or, they are part of the cause of the multiple challenges that need solving, and it is unlikely that as causes of the problems they will be part of the solutions. It is therefore clear that a massive rethink and redesign of agriculture and horticulture is required.

It is hoped that the ideas and concepts in this report will provide some alternative ideas and answers to these multiple challenges, such as: non-chemical solutions to the use of herbicides for undervine vegetation elimination, ideally replacing them with a ground cover of living plants to protect the soil and increase its health, while also sequestering atmospheric carbon dioxide. The reduction or elimination of the need for nitrogen fertilisers through the use of legumes for biological nitrogen fixation. A reduction in pesticide use through conservation biocontrol, and, increased biodiversity, both directly through an increase in deliberately sown plant species, but, indirectly through tolerating a wider range of self introduced plants, and through the greater range of soil biology and non-harmful insects that are a result of increased plant diversity. Non of these will solve all the challenges humanity faces, but, they all are parts of the solutions required.

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