An introduction to the principles of service (cover) crops and intercropping

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Dr Charles N Merfield. MRSNZ

The BHU Future Farming Centre

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1. Introduction

Service crops, also known as cover crops and non-cash crops and the practice of intercropping are increasingly important tools to address multiple objectives in agriculture and horticulture, such as:

- Increasing cash crop yields and thereby profit
- Increasing soil organic carbon and boosting soil health
- Reducing nutrient losses to save fertiliser and protect water quality
- Weed, pest and pathogen management thus reducing pesticide use and cost
- Biological nitrogen fixation thus reducing nitrogen fertiliser costs
- Reducing erosion, keeping soil on the farm and out of waterways
- Managing soil moisture

Indeed there are so many different names, benefits, uses, approaches and options that it can be quite confusing for newcomers. This report is therefore a beginners guide to the principles of service crops and intercropping. It provides links to some of the key further sources of information. Indeed there is so much information on service and intercrops that sifting the wheat from the chaff is the main problem. This report therefore also takes a different approach to most other sources of information. Instead of listing species and descriptions, it looks 'under the hood' at the ecological foundations and mechanisms of service and particularly intercrops. Looking from this more fundamental perspective hopefully opens up the ability to conceive of new approaches and methods, rather than just replicating current techniques. It therefore does not give detailed prescriptions of individual service and intercrops as this is not possible at a high level, what works well in one location works badly in another - farming is variable - and there are plenty of other sources that do exactly that.

Service crops are also not a new idea, in 1927 Pieters (1927) published 'Green manuring principles and practice' at a comprehensive 267 pages with 352 references, which in turn detailed historical uses of service crops going back to ancient times. Neither is intercropping novel, for example, prior to the advent of pesticides and widespread uptake of nitrogen fertiliser from the 1940s onwards, most of the corn and soya grown in the USA was intercropped. It is only with the advent of intensive agriculture and the green revolution post the second world war that both service crops and intercropping fell out of favour and monocultures took over. With the increasing challenges facing farming, such as resistance to pesticides, a need to reduce environmental impacts and the rising cost of fertiliser, service crops and intercropping are making a valuable comeback.

2. Service crops

2.1. Service crops: What's in a name?

The first confusing thing about service crops is all the different names used. Adding to the confusion is there is no agreed definition of the names, different people use the same term to mean different things, and, the meanings have changed over time, for example what was called a green manure in the early 1900s is now often called a cover crop.

'Cover crops' is the common name for service crops but it is used both as an overarching term and as a specific type of service crop who's primary purpose is to cover the soil. Due to this confusion, alternative terms are increasingly used for the umbrella term for all the different types of cover cropping.

'Non-cash crops' is a common alternative to 'cover crop' but hardly rolls off the tongue and does not indicate what they are for - just they are not cash crops.

‘Subsidiary crop’ is increasingly used in Europe and was used in the past to mean a companion crop (Pieters 1927, p 228). It is however something of a mouthful and an uncommon word.

‘Companion crop’ is now the preferred name by the United Kingdom Government, but, not all companion crops accompany a cash crop which is confusing. ‘Companion crop’ and ‘companion plants’ also has particular connotations in organic gardening about specific plant pairings with beneficial effects, e.g., planting garlic next to roses to keep aphids off the roses, which have largely be disproved by scientific research. It therefore has baggage.

Service crops as a name is simple, and states what its purpose is: to provide services to the rest of the farm system, e.g., (Garcia *et al.*, 2018). It also aligns it with ‘ecosystem services’. Some researchers are even going so far as calling them agroecological service crops, e.g., (Navarro-Miró *et al.*, 2019).

‘Cover crop’ as a term also has strong association with annual plant species, such that a perennial living mulch would not commonly be called a ‘cover crop’ but it clearly is a ‘service crop’. ‘Service crop’ is therefore a broader and more encompassing term. Therefore anything that is not a cash crops (e.g., vegetables, cereals, fruit, pasture and other crops grown to feed to animals, etc.) is likely to be a service crop.

The term ‘service crop’ also does not come with much prior meaning or baggage so people tend to make less assumptions about it, than they would with terms such as cover crop and green manure. Hence why this report uses ‘service crops’ as the overarching term.

2.2. Multiple benefits of service crops

There are multiple types of service crops with each having a main purpose, e.g., covering the soil or fixing nitrogen. However, while they may have a main purpose, as they are living plants they can’t avoid producing multiple outcomes. For example, a green manure planted to fix nitrogen, will cover the soil as well, and provide resources for beneficial insects. So while any given service crop has a main purpose, many other benefits accrue too.

2.3. Service crops are named for their outcomes

Service crops are mostly named for the outcome they are planted to achieve not the crop species that are used. So, the same plant species, e.g., oats, could be called a cover crop, a catch crop, or a smother crop, depending on the objective it was planted for.

This report while sticking to the most common definitions also pushes the boundaries with some terms and forms of service crop, in an attempt to broaden thinking around what is a service crop and what purposes they can be put to. It is stated which terms are less commonly used.

2.4. Species used

A wide range of plant species are used as service crops. However, most tend to be annual arable crops and pasture species. This is because seed is readily available, and inexpensive, or at least not highly expensive. This is particularly important for annual service crops, which may be only grown for a few months, so using expensive seed is cost prohibitive, compared to the benefits gained. Pasture species, being mostly perennial, are mainly used in perennial cropping, e.g., top-fruit, nut trees, as living mulches in the crop row (intrarow) and as pasture in the alleyways (interrow).

Arable and pasture species are also often quick growing, robust, competitive and produce large amounts of biomass, which are often important attributes of service crops.

2.5. Service crops need looking after

A common mistake when starting out with service crops is thinking that they can look after themselves. However, while they can do OK with minimal attention, they are still crops and to get the best performance out of them they still need some looking after. Key is ensuring soil nutrient levels are correct, and if the service crop does not contain any legumes at all, or its not a catch crop, then nitrogen fertiliser may be required also. Particularly if mixtures are being used, pests and pathogens should not be a problem and a higher tolerance of infestations and infections can be accepted as they wont be used for food or fodder. Large amounts of pests or pathogens, especially if they could impact the wider farm system, will need to be managed, potentially by early termination. With a good strong diverse service crop, weeds should not be an issue, but, if they are, then their impact on the following crop and longer term impacts, e.g., building up the weed seedbank in the soil need to be weighed up against weed control. Again early termination is an option and an alternative to herbicides.

2.6. Types of plants - functional groups

The plants used for service crops are often divided into functional plant groups - which are simply plants that share similar characteristics. There are three main functional groups: grasses, legumes and forbs (herbs) i.e., everything that is not a legume or grass. Grasses key ability is that they have fine, fibrous root systems that are good at binding and aggregating soil. Legumes key ability is fixing atmospheric nitrogen, some of which is quickly available to non-legume plants and soil biology in general, resulting in increased growth of those plants and boosting soil biology. Forbs are so diverse no general comments can be made about them, it is down to the benefits specific species bring. Generally mixing a grass and a legume is considered to be the base for many service crops, with forbs then added for a range of benefits, e.g., tap roots that can penetrate deep into the soil to break up tillage / cultivation pans. Some times more than three functional plant groupings are defined, e.g., deep tap roots vs. shallow roots, but this is less common.

2.7. The importance of plant diversity

Soil and ecological science is showing that increasing plant diversity has multiple benefits both to the production system and wider environment (Tamburini *et al.*, 2020). There is therefore a growing interest in increasing the number of plant species in service crops. When the number of species exceeds seven to ten species it is often described as 'diverse'. Below that number the crop is often just described as a mixture. Mixtures of 20 to 30 species are increasingly being used.

2.8. The importance of root exudates

There has been a revolution over the last decade in soil science regarding organic matter formation and the drivers of soil biology (Cotrufo *et al.*, 2022; Merfield, 2023). It is now considered that dead residues from plants, both roots and foliage, and other organic sources (e.g., manure) only contribute to about 20% of soil organic matter, and that this decays relatively quickly over a few years to few decades at most. Organic matter formed from dead residues is called particulate organic matter (POM). In addition 'humus' meaning recalcitrant organic matter made up of large complex molecules, which used to be viewed as the foundation of soil health, is now considered to not exist. Instead it is root exudates, composed of simple soluble organic compounds such as carbohydrates and proteins that are the primary source of soil organic matter. These exudates are food for soil microbes that live mutualistically (see section 4.1.1) around plant roots. Some of the exudates and other material end up in tiny spaces inside soil particles, particularly clays, where they are protected from further decay due to being out of reach of the soil microbes. This is called mineral associated organic matter (MAOM). MAOM makes up about 80% of the organic matter in soil and persists for centuries to millennia.

This new soil organic matter paradigm completely changes how service and all crops should be viewed. It is not the residues, particularly from foliage, that drives organic matter formation, soil biology and therefore soil health, it is exudates from living roots that are the most important. The organic matter from residues decomposes in a few years, while the organic matter from root exudates dominates soil organic matter levels and lasts for centuries. Where soil health and organic matter / organic carbon levels are a driver for the use of service crops, the focus must be on the roots and their production of exudate, rather than aboveground biomass production.

Regarding rood exudates there is a critical difference between annuals (e.g., arable crops) and perennials (e.g., pasture). Annuals put most of their resources into growing foliage and seed, so produce far less roots and root exudates than perennials which put most their resources into roots and root exudates. Annuals also only live for a few months, perennials are present for many years. Therefore perennials beat annuals hands down for soil biology, organic mater and health. Therefore never replace perennials with annuals if the aim of using service crops is soil health.

2.9. Termination

A range of techniques are used for terminating service crops.

Grazing with livestock is commonly used and has the extra benefit of feeding the stock and converting the foliage into urine and dung which contain plant available nutrients, esp. nitrogen and organic forms of nutrients that can be easily mineralised into plant available forms. This contrasts with the crop residue which has a higher C:N ratio (contains a higher percentage of carbon) than dung and urine, which means that it will take longer to decompose and release crop available N and other nutrients. Foliage such as straw with high C:N ratios can cause nitrogen robbery when incorporated into the soil due to microbes using up soil N to decompose the high carbon compounds. Grazing minimises the risk of N robbery. Where equipment e.g., planters, are unable to cope with large amounts of residue, grazing is an effective way of managing it. However, grazing means the foliage is decomposed in the livestock's digestive system, not by soil biology, and there are concerns that soil biology may not benefit as much. But, there is little research comparing livestock vs. non-livestock termination on soil properties, especially over the longer term. In addition as plant root exudates are the main source of soil organic matter and energy for soil biology not aboveground foliage, the value of above ground residues on soil health has been over-estimated.

Herbicides are commonly used for termination, particularly for crops that will regrow from termination techniques such as grazing and mowing. Herbicides are also used in combination with termination techniques such as crimper rolling (see smother crops below) to ensure effective kill.

Mowing, particularly flail mowing, is used where the crop is to be tilled / cultivated into the soil.

In colder climates for over winter cover crops frost sensitive species are killed by winter cold / frost.

There are other specialised techniques, e.g., crimper rollers, that are discussed under individual service crops.

Some plant species, e.g., ryecorn, release allelochemicals (see section 4.1.3) when they are growing and/or when they are terminated that can inhibit the germination of both crop and weed seeds. Where this occurs sufficient time (between two to six weeks) has to elapse between termination and planting the following crop.

Terminating a service crop several weeks before establishment of the following crop can also be useful to allow the residue to start rotting and breaking down making it easier to till / cultivate into the soil and/or make it easier to plant through.

3. Types of service crops

3.1. Cover crops

The aim of cover crops is to cover and protect the soil, as well as increasing soil health, e.g., aggregate stability and organic matter / organic carbon. The concept of cover crops is linked with conservation agriculture[1] which was developed in the United States to address the Dust Bowl[2]. Cover crops are thus the opposite of a bare fallow where soil is tilled / cultivated over a period of weeks to months to eliminate all vegetation leaving the soil bare. Soil science is very clear that fallows are exceptionally detrimental to soil quality / health, and they also reduce many ecosystem services. Poor quality soil is unable to grow as productive and profitable crops as good quality soil, and is more prone to erosion by wind and rain. Cover crops protect the soil surface from wind and rain drop impact, increase infiltration rates and slow water movement over the soil surface. The roots also hold soil together and provide energy and organic compounds to soil microbes, which are the foundation for all soil biology. A wide range of species are used in cover crops, however, including at least one grass is important for the soil binding abilities of their fine fibrous roots, and one legume for N fixation, is considered important.

Cover crops can be grown at any time of year, though they are most commonly grown over winter to replace a bare fallow or any other time there is no cash crop in the ground. They are also increasingly being grown for very short periods of time, e.g., a few weeks, particularly in summer, to ensure there are living roots in the soil at all times, to maintain soil biology and health. This is sometimes described as 'chasing the combine with the drill'.

3.2. Green manures

As noted in the introduction the term green manure has changed over time. The terms cover crop and green manure are also sometimes still used interchangeably. Generally green manure is now used to mean a service crop than is grown with the primary aim of fixing atmospheric nitrogen (N) to increase soil N, and to also improve soil health. This is done through growing leguminous species such as beans and clovers. The legumes can be in pure stands, or more commonly as part of a mixture of species. Counterintuitively, more N can be fixed by a legume intercrop, particularly with grasses, as the non-legume takes up available soil N, which is then unavailable to the legume which forces the legume to fix more nitrogen. This is because legumes will use soil N in preference to fixed N due to the energy required for fixation. Legumes vary in how much N they will fix in the presence of soil N. Some will stop fixation entirely, others will continue to fix some N regardless of soil N levels. This is a key reason for the enhanced performance of cash intercrops with legumes, e.g., wheat and peas, and why legumes are so common as intercrops, both cash and service crops.

Nitrogen fixation can only occur above 'biologic zero' a soil temperature between 5 to 10°C. Below this it is too cold for the biochemical reactions that fix atmospheric N. Therefore in temperate climates little fixation occurs in winter. For overwintered green manures in cooler climates nearly all the N fixation therefore occurs in spring in the last few weeks of the green manure's life before termination. Traditionally green manures have been grown over winter, but, as the amount of N fixed overwinter may be small, they are increasingly grown during the main cropping season to maximise N fixation.

Legumes need the correct bacteria species to fix the nitrogen. Where a legume species has been grown before, or another species that share the same bacteria, then the correct bacteria species will

[1] www.fao.org/conservation-agriculture/en/ and wikipedia.org/wiki/Conservation_agriculture
[2] wikipedia.org/wiki/Dust_Bowl

be present in the soil. If not, it is likely that the seed will need inoculating with the correct bacteria at sowing.

In North America green manuring is also used to describe a service crop that has been tilled / cultivated into the soil, which is how Pieters (1927) also defined green manure.

3.3. Catch crops

Catch crops are grown to 'catch' / absorb through their roots, nutrients that would otherwise be lost through leaching. The nutrients are principally nitrate and to a lesser extent orthophosphate (soluble phosphate). The main types of plants used in catch crops are quick growing grasses, particularly cereals and annual pasture grasses, and the mustard family (Brassicaceae / Cruciferae). As legumes fix atmospheric nitrogen and thus increase soil nitrogen, they would appear to be unsuited to use as a catch crop, especially by themselves. However, in intercrops with grasses they have been shown to reduce nitrate losses more than grasses alone (Vogeler *et al.*, 2019).

Nutrient leaching occurs when soil moisture exceeds soil capacity and water thus starts to drain from the soil. In temperate regions that mostly means winter when plant growth is slow. It is therefore important to establish the catch crop sufficiently in advance of when leaching will start so the plants have enough roots, and roots deep enough in the soil profile, to take up the nutrients at depth.

3.4. Mulch crops

Mulch crop is a less common term, here it means a service crop that is grown with the aim of creating a dead mulch on the soil surface from the mulch crop's above ground residues, then planting a cash crop into the mulch. Mulch crops are often just called cover crops. Mulch crops are based on annual species, typically a cereal that produces a large amount of aerial biomass such as oats, triticale and particularly ryecorn. These are mixed with a tall or climbing legume for nitrogen fixation to boost overall biomass yield, e.g., vetches and tic (faba) beans.

Mulch crops are typically grown overwinter for termination in spring as they need sufficient time to achieve a large biomass.

Termination method is an important factor as it needs to allow for planting machinery to plant through the mulch. An increasingly common technique for doing this are crimper rollers (Figure 1), which consist of a metal roller with vanes on it that bend and crimp the crop stem.

Figure 1. Helical blade roller crimper.

For certain plant species, when they have moved from vegetative growth to reproductive growth, i.e., are at or have passed full flowering (anthesis) crimping will kill them. However, many plant species are not killed by crimping at all, regardless of the stage of growth. There are many factors that must be taken into account to achieve successful crimping, cash crop establishment and growth. It is therefore quite technical and there is a high potential for failure if all factors are not correctly managed.

3.5. Living mulch

A living mulch is where a soil covering mulch is created from living plants, that are shorter, often considerably shorter than the cash crop. They are typically grown for weed suppression, soil protection and fixing N for the cash crop. Ideally the living mulch boosts crop growth though positive symbiosis (see section 4.1.1).

They are used under perennial crops such as fruit trees, and in this situation typically perennial pasture species are used for the living mulch. Tap rooted legumes are commonly used as these are thought less likely to compete with the cash crop, as their roots are in a different soil volume to the shallow feeder roots of most woody cash crops, and they fix nitrogen which becomes available to the cash crop.

They are also grown under annual crops, such as cereals and larger vegetables, e.g., courgettes / zucchini and cabbages. In annual crops the time of establishing the living mulch is often critical in managing competition with the cash crop (see section 5.3.3). In annual crops the living mulch is often retained when the cash crop is harvested, e.g., to maintain soil protection, particularly over winter.

Another approach for annual cash crops is drilling into a perennial living much, e.g., white clover. Unless correctly managed the living mulch will strongly compete with the cash crop and significantly reduce yield, even completely out compete the cash crop and kill it. Hard grazing or low mowing is often used to set the living mulch back, however, this only reduces aboveground competition for a short period and does little for root competition (see section 4.1.3) which is more important, particularly for a newly establishing cash crop. To give the cash crop the best start, the living mulch most likely needs to be killed in the crop row or significantly set-back. Banded herbicides and strip tillage can be useful for this.

3.6. Smother crops

Smother crops are grown to smother weeds, particularly problematic weeds that are hard to kill, especially when herbicides can't be used. Smother crop is a moderately common term, with cover crop also being used to describe them. They use the same plant species and functional groups as mulch crops, as both rely on producing large amounts of aerial biomass. In some situations perennial pasture species are used, for example red clover.

To be effective, smother crops need to be growing when the problem weeds are also growing so they can out-compete them. Ideally they need to be established at such a time that when the weeds are starting to grow, the smother crop is already well established and therefore competitive against the weeds. This means most smother crops are grown over the main cropping season. As discussed in section 4.1 the majority of plant competition occurs underground, so, root competition, as well as foliar competition needs to be considered, e.g., that the smother crop's roots are in the same soil volume as the weeds root system.

Any suitable termination method can be used.

3.7. Conservation biocontrol crops

Conservation biocontrol[3] is where plant species are grown to boost the populations and fecundity (production of offspring) of natural enemies of crop pests so pest populations are reduced, ideally below economic thresholds. Conservation biocontrol is a substantial science and practice, and, is growing in popularity due to the challenges facing agrichemical pest control. Conservation biocontrol crops have not traditionally been considered to be cover crops in the broad meaning, but, they do fall under the concept of service crops They are however increasingly being grouped with cover crops in North America. They are included in this report to inform readers of the concept, to make a link between conservation biocontrol and service crops as a whole, and to illustrate the multifunctionality of service crops.

'Companion crops' and 'companion plants' are also used to describe conservation biocontrol crops. While this is considered an accurate term in this context, as noted in section 2.1, the term has prior connotations in organic gardening that are considered unhelpful.

The spatial arrangement of the cash and conservation biocontrol crops is important. The conservation biocontrol crop plants need to be close enough to the cash crop that the natural enemies can move from the biocontrol plants to the cash crop plants. This distance varies with the natural enemies, from a few meters for species such as small predatory mites (which cannot fly) to hundreds of meters, even kilometres for actively flying species. A wide range of arrangements are therefore used, from having the biocontrol plants under the crop, which is common in perennial cash crops and also cereals, having low densities of plants throughout the cash crop, to rows through the cash crop and around field edges.

3.7.1. Shelter, nectar, alternative prey, pollen (SNAP) crops

SNAP is an acronym for shelter, nectar, alternative prey, pollen coined by the late Distinguished Professor Steve Wratten (Barnes *et al.*, 2009). These are key resources required by many natural enemies to fully prosper and minimise crop pests. SNAP crops therefore provide these resources. SNAP crops are also called insectary crops in North America.

3.7.2. Banker crops

Banker crops, or more commonly banker plants, host an alternative prey species of a natural enemy so that the natural enemy's population is boosted, especially when the natural enemy's prey species that attacks the cash crop is absent or at low levels. For example, lucerne / alfalfa is grown around and through cereals, which hosts aphids that are parasitised by parasitic wasps which increases their population, so they can reduce the aphid population on the cereal crop. Key is that the aphids that feed on lucerne cannot feed on cereals, so there is no risk to the cereals from the aphids on the lucerne.

3.7.3. Trap crops

Trap crops are more attractive to arthropod ('insect') pests than the cash crop, therefore 'trapping' the pest in the trap crop, and keeping it away from the cash crop. A wide range of trap crop management approaches exist, key to which is preventing the trap crop becoming a source of pests that then attack the cash crop.

'Dead-end' trap crops are those on which the pest is killed, or cannot complete its lifecycle, therefore reducing the pests population (Shelton & Nault, 2004).

[3] https://en.wikipedia.org/wiki/Biological_pest_control#Conservation

Trap crops are also occasionally called sacrificial crops, i.e., they are sacrificed for the benefit of the main crop.

3.7.4. Repellent crops

Repellent crops repel arthropod pests, mostly due to allelochemicals (see section 4.1.3) that they release from foliage and/or roots. They are planted around the outside of a cash crop to prevent the pest entering the crop, and / or the are planted among the cash crop plants to repel pests out of the cash crop.

3.7.5. Push-pull crops

Push-pull crops are a combination of trap and repellent crops. The repellent crop 'pushes' the pest to the trap crop which is also 'pulling' the pest in.

3.8. Sentinel crops

Sentinel crops are a less common service crop. They are plant species that are more susceptible to a pest or pathogen than the cash crop, and/or they emerge and grow quicker, so they get attacked before the cash crop, allowing the pest or pathogen to be detected earlier than if only the cash crop were present. For example, rape planted in wheat for detecting slugs. This allows more timely crop protection measures to be undertaken. They are typically sown at low densities randomly throughout the crop. If they could become a problem if left to grow with the crop, they are typically terminated using selective herbicides once their job is done.

3.9. Nurse crops

Nurse crop is also a less common term. It is where one crop provides protection, typically against wind, but also shade from sun, retaining soil moisture, etc., to help the cash crop become established. The term is mainly associated with establishing trees, but, is also used in annual crops, e.g., cereals to protect salad crops from wind-blown sand.

3.10. Biofumigation crops

Biofumigation crops are specific cultivars of a small number of species, e.g. mustard (*Sinapis* spp.) that contain high levels of pesticidal chemicals. When the biofumigation crop is chopped up and incorporated into the soil, the pesticidal chemicals form a gas which fumigates the soil, killing pests, pathogens and some weed seeds. While effective, biofumication crops are typically monocultures, they are short term, incorporated when still green, use deep and intensive cultivation (e.g., rotery hoe, rotery spader), the soil needs to be rolled and packed and is left bare for at least two weeks. The fumigants also kill good as well as bad soil organisms. These multiple negative aspects of biofumigation mean it a technique of last resourt, and an indication that the farm system needs to be improved, e.g., increase rotational diversity.

3.11. Service crop conclusions

These examples show that service crops are highly diverse in their functions and how they are used. While extensive, the list is not considered exhaustive, as new service crop types and approaches continue to be developed.

4. Intercropping

4.1. An intercropping primer

Intercropping is an all-encompassing term for where two or more different plant species - crops - are grown, both simultaneously and close enough so that biological interactions can occur. Intercropping also goes by a range of other names including crop mixtures, companion planting, multi-cropping, co-cultivation, polycultures, interseeding, , interplanting, interrow-planting, undersowing and underplanting.

The crops can be both cash crops or service crops. For example a mix of two cash crops such as wheat and beans, or a cash and service crop such as wheat and a clover. The number of species in an intercrop is only limited by the objectives and practicalities.

There are a range of benefits of intercropping. For example, intercrops can use resources such as light, water, and nutrients more efficiently than single crops planted in separate areas. This can increase yields and profit. Intercrops often have fewer insect pests, pathogens and weeds and some are used specifically for these purposes. Intercrops are used to protect soil which would otherwise be bare under a cash crop. Intercropping also allows more effective management of service crops. However, these benefits require good understanding and management to be successful. Key to that understanding is ecology.

4.1.1. Symbiosis and ecological niches

Intercropping is based on the ecological concept of symbiosis, which comes from the Greek for 'living together'. Symbiosis is where organisms interact with each other, in positive, negative and neutral ways. There are six forms of symbiosis: mutualism, commensalism, parasitism, neutralism, amensalism and competition (Figure 2).

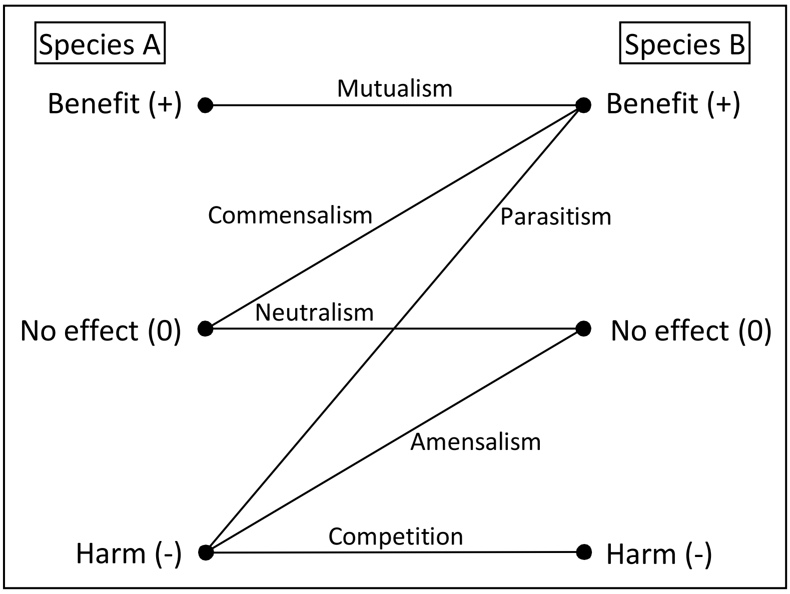

Figure 2. The six possible types of symbiotic relationship, from mutual benefit to mutual harm.

The aim of intercropping is to get positive (mutualism), mixed (commensalism) or neutral (neutralism) interactions between cash crop species. Where a service crop is supporting a cash crop then it is acceptable for the service crop to be harmed (amensalism).

The second ecological concept supporting intercropping is the 'ecological niche'. This describes how a species or organism fit into a specific environmental condition, e.g., what volume of soil their roots occupy.

4.1.2. Monocultures vs. multicultures

Looking at monocultures through the ecological lenses of niches and symbiosis finds that as all the plants are identical they all occupy the same niche (such as root type) so they strongly compete with each other, i.e., have negative symbiosis. Growing two or more plants that have complementary niches often results in positive symbiotic effects so they boost each others growth, or at least one boosts the growth of the other.

The idea behind monocultures is therefore simple but misleading. The idea is that to maximise yield a range of plant species or cultivars are grown in monocultures to see which yields the most. Then only the highest yielding species or cultivar is grown in monoculture because if the highest yielding one was mixed with one or more that yields less, the yield of the mixture would be the mathematical average of the monoculture yields of the plants in the mix. Simple but wrong, because it fails to take symbiosis and niche complementarity into account.

Two terms are used in intercropping to describe the effects of beneficial symbiosis: overyielding and transgressive overyielding. Overyielding is where the yield of the intercrop is greater than the mathematical average of the monoculture yields. Transgressive overyielding is where the intercrop yields more than the monoculture yield of the highest yielding component of the intercrop! It's called transgressive because it transgresses the orthodoxy of yield - that monocultures yield the most. Transgressive overyielding is also common. Intercrops often yield more than then best monoculture.

There are also the opposite terms, underyielding and transgressive underyielding where the intercrop yields less than the mathematical average or may be lower than the lowest yielding monocultures. So the correct intercrop species are required to get yield increases. This highlights the importance of the two rules of intercropping: Everyone's mileage varies and thus don't bet the farm on a new intercrop, things could go badly wrong. Always try intercropping on a small area to start with, and test over several fields and/or years before scaling up.

4.1.3. Plant interactions - aboveground and belowground

How plants interact (both support and compete) with each other is key to whether they will make good intercrops. Interactions occur both above and belowground. Aboveground competition is mostly for sunlight, belowground interactions are for water, nutrients, connections with soil biology, e.g., mycorrhizae fungi and allelopathy. Being out of sight, underground interactions are often out of mind, but, underground interactions are frequently much more important than aboveground. However, the science of plant root interactions is comparatively limited as it is difficult to study in realistic situations and some of the older research methods are believed to create false results. What is increasingly clear from more recent research is that it is not just competition for water and nutrients that is important but allelopathy has a critical role. Allelopathy is commonly thought of as one plant suppressing another, but, like symbiosis, the term allelopathy is neutral. It is where one organism produces one or more allelochemicals (biological chemicals) that influence the germination, growth, survival, and reproduction of other organisms. It can be both beneficial (positive allelopathy) or detrimental (negative allelopathy). As more research is undertaken, the more complex allelopathy is discovered to be, with, lots of multifaceted chemical communication occurring in the soil among many organisms, not just plants. This means that theories about underground interactions are probably too simplistic, e.g., if the species in an intercrop occupy different soil volumes then competition should be limited. It may even be that allelopathic interactions differ at the cultivar level not just species level. Thus the only way to determine what makes good intercrop plants is trial and error i.e., experiment, and, what makes for good and bad intercrops may be cultivar specific, for both the cash and service crops.

5. Intercrops types

The same as there are lots of different types of service crops there are multiple intercropping approaches. The types of agronomic practices that are considered to be intercropping in this report has also been pushed to the limit, and includes techniques that are not commonly thought of as intercropping. This is aiming to broaden the conception of intercropping so new approaches can be imagined and developed.

There are four main variables in intercropping:

- Plant species
- Proportion of species
- Spatial arrangement
- Temporal relationships

Within each variable there are lots of options, and therefore lots of flexibility and also complexity which limits what can be worked out theoretically. As noted before, working out what is likely to be a good intercrop, is part experience of what has worked before, some rules of thumb about what is likely to work in a new intercrop, and then trial and error - in-field testing in multiple small areas over several years, to see what does work and what does not, before scaling up.

5.1. Plant species

There are few hard and fast rules about what makes a good mixture of species. A grass and a legume is often viewed as the foundation of many intercrops. Mixing plants with different morphologies (form and structure) is a common approach. However, as noted in the section on symbiosis (above) allelopathic interactions may be important. As these can't be seen or predicated and are mostly unstudied, trial and error is again the only way to find a good mix of species.

5.2. Proportions of species in intercrops

The starting point for the proportion of species in an intercrop, especially where they are randomly mixed together, is to divide the target plant population of the monoculture by the number of species in the intercrop, e.g., if there are four species in the intercrop, each needs to be ¼ of its monoculture population. While this can have good results, some species are more competitive than others, and when sown at this proportional rate they can dominate the intercrop. The percentage of plants for a given species is therefore often adjusted up or down depending on how competitive it is.

Other factors also drive the proportion of the species. For example, in a green manure, where nitrogen fixation is the primary objective, legumes may make up the majority, e.g., 75% of the plant population and non-legumes the other 25%. Similarly where the outcomes are provided by specific species, e.g., deep penetration of roots, those species will form a larger percentage of the intercrop.

And sometimes practical considerations, such as some species being expensive mean they form only a small proportion of the intercrop. Therefore there are also few hard and fast rules about proportion of species to put in an intercrop, just past experience and more trial and error.

5.3. Spatial intercrop arrangements

There are range of spatial intercrop arrangements going from random mixing of plants through to the landscape scale. Different component of the intercrop can also have different spatial arrangements, for example, annual row crops with a random broadcast undersowing, and agroforestry with tree lines interspersed by pasture or row crops.

5.3.1. Random intercrops

Random mixing, also known as maslin, is where planting seed is mixed prior to sowing. It's commonly used in pasture and service crops such as cover crops. It has been shown to increase inter-plant competition and reduce yield than more structured layouts such as checkerboard planting of arable crops.

5.3.2. Structured intercrops

In very intensive production systems such as urban farms and manually managed market gardens, structured intercrops can be used. For example, taller crops are planted furthest from the earths equator, i.e., so they are furthest from the midday sun, and progressively shorter crops planted sequentially in front of them, thus maximising sunlight interception. Or an orderly repeating arrangement as is used in the 'Three Sisters' intercrop of maize, climbing beans and squash. Work at Wageningen University in the Netherlands has been researching pixel cropping[4] (also known as pixel farming, pixelfarming, or pixelteelt in Dutch) where vegetable plants and service crop plants are arranged individually (Ditzler & Driessen, 2022).

5.3.3. Undersowing

Undersowing, underplanting, oversowing, and overplanting, are the same thing. This is where a lower growing crop, is sown under a taller established crop. Often the taller crop is a cash crop and the undersown crop is a service crop, though service crops are also undersown, particularly if they are being used as a nurse crop (see below).

Often the undersown crop is broadcast, particularly into narrower row arable crops. As the undersown crop is broadcast it is a random intercrop, within the structured rows of the primary crop. This is one example of different intercrop components having different spatial arrangements.

Undersowing can be a particularly valuable approach for establishing pasture under an arable crop, as the pasture is already established when the arable crop is harvested, so no post harvest and planting activities are required. The arable crop also acts as a nurse crop for the pasture, though, it does also compete / suppress it as well as time progresses. When the competition from the arable crop is eliminated by harvest the pasture rapidly develops. This can give weeks even months of extra pasture growth. Likewise an annual cover crop can include perennial pasture species, such, that when the cover crop is terminated the perennial pasture species take over.

Undersowing is also a key technique in perennial crops for establishing living mulches in the crop row. It is also used for establishing living mulches under annual crops, particularly arable crops, especially those on wider spaced rows such as maize and soya.

Undersowing often has a temporal relationship as well in terms of when the undersown crop is established compared with the main crop (see section 5.4.2).

5.3.4. Row intercropping

Row intercropping is where individual crop rows, or a few rows, are sown as monocultures, with adjacent rows or groups of rows, being different species. This is typically done for wider row cash crops such as maize and soya, but, with the right drilling equipment it can also be done for cereal crops. For example, with RTK GPS systems the tractor and drill can be moved half or even smaller fractions of the interrow spacing sideways, allowing different species to be drilled in adjacent rows on different passes. This multi-pass approach overlaps with interrow-planting / checkerboard planting, discussed below.

[4] https://www.wur.nl/en/project/Pixel-cropping.htm

In vegetables, esp. intensive market garden cash crops, row intercropping can be done for both drilled and transplanted crops with the right equipment and also when manually planting.

5.3.5. Interrow-planting and checkerboard intercropping

Interrow-planting or checkerboard planting is a valuable weed management technique for monocultures and intercrops. It involves halving the sowing rate of the drill, then, for checkerboard the field is drilled twice at right angles, or where that is impossible down to around 45°. For interrow-planting the drill is offset by half a drill width so that the second drill pass drills the crop in the middle of the first drill passes interrow. This decreases rectangularity enabling faster crop canopy closure which suppresses weed seed germination.

The same techniques can be used for intercropping with one crop species or mixture sown in one pass, and the other species or mixture sown in the second pass. This can be particularly helpful where there is large difference in seed sizes, and/or sowing depths. The larger seeds are sown first at a deeper depth and then the smaller seeds are sown over the top at a shallower depths.

5.3.6. Strip intercropping

Strip intercropping is where a monoculture is sown in one or multiple drill widths or vegetable beds. While this reduces the direct interaction between individual crop plants, there are still synergistic effects at the field level, particularly for pest and pathogens but also crop growth and yield. Strip intercropping eliminates the complexities created by more intimate intercrops, particularly around planting, harvesting and use of agrichemicals.

Wageningen University has done extensive and detailed research on strip intercropping and found a wide range of benefits (Apeldoorn, 2021).

5.3.7. Agroforestry

Agroforestry is the planting of low density woody vegetation, typically trees, in pasture or cropping systems. Pasture agroforestry is called silvopasture, cropping is called silvoarable and with mixed farming agrosilvopastoral. Trees are typically planted in widely spaced rows, e.g., 20 to 60 m apart with densities of 50 to a few hundred trees a ha, with the pasture or crops grown in the 'alleyways' between the tree rows (Figure 3).

Figure 3. The INRA Vézénobres Agroforestry research site in France. From (Briggs, 2012).

Agroforestry is therefore an 'extreme' form of intercropping as one cash crop, the trees, typically grow for many years to decades, which the other intercrops are short term, particularly annual arable and vegetable crop. There are copious benefits to agroforestry, both to the wider environment and to the production system, such that there should be much greater use of it (Dagar & Tewari, 2018).

5.3.8. Landscape scale intercropping

There is increasing research showing that the landscape that a farm / orchard / vineyard etc., is located within has a significant impact on pests, pathogens and even weeds. More diverse landscapes, which typically means more diverse farms (as farms make up much of the landscape in agricultural areas) reduces pests, pathogens and weeds (Lichtenberg *et al.*, 2017; Lindell *et al.*, 2018). The diversity of the farmed landscape can therefore be considered a form of intercropping at the largest scales.

5.4. Temporal intercrop relationships

Intercrops vary not only in their spatial arrangements but also across time.

5.4.1. Concurrent intercrops

Concurrent intercrops are where all the crops are planted and harvested / terminated at the same time. For example, a bicrop of oats and peas, or, a mixed species cover crop. This is therefore the simplest temporal relationship.

5.4.2. Delayed intercrops

Delayed sowing in intercrops is used to manage competition and maturity dates. For example, where two or more cash crops are being intercropped but they have different growth durations, such, that if they were sown at the same time they would not mature together thereby complicating harvest. One or more of the crops is therefore sown with a delay of days to a few weeks after the first crop is sown. This typically requires the use of row intercropping, interrow-planting or checkerboard drilling, to minimise damage to the first sown crop, especially if it has emerged.

Another example, is a cash crop undersown (see below) with a service crop, which if the service crop was sown with the cash crop it would be too competitive, so, the establishment of the service crop is delayed to give the cash crop the competitive advantage.

5.4.3. Undersowing intercrops

Undersowing is both a spatial and temporal form of intercropping, with the undersown crop established after the main crop has emerged and started growing. Traditionally undersowing is taken to mean that the undersown crop is established while the main crop is still relatively young. However, it is also increasing being used to describe establishment of the service crop later in the life of the main crop. The term undersowing is mostly used when the undersown crop is a service crop, where a cash crop is established later in a previous crop it is mostly called relay cropping.

5.4.4. Relay intercropping

Relay cropping is where a cash crop is established shortly before harvest of a preceding cash crop. It is more common in wider spaced crops such as maize and soya and typically used no-till seeding equipment, or strip tillage. The following crop is typically sown in-between the rows of the proceeding crop.

5.4.5. Sowing green

Sowing green is a term from regenerative agriculture, and has the same timing as relay cropping, i.e., sowing shortly before harvest or termination. It has the key aim of maintaining living roots in the soil, to support soil microorganisms, esp. those that are dependent on plant roots such as mycorrhizae fungi. The preceding crop is typically terminated using broad spectrum herbicides just before the following crop emerges.

5.5. Agroforestry

As for spatial arrangements, agroforestry can be considered as an extreme form of temporal intercropping, with the woody crop growing for many years, even decades, while the pasture or annual cash crops may grow for only a few months or a few years.

6. Conclusions

Service crops and intercropping through using different plant species, mixtures of species and manipulating spatial and temporal arrangements provide powerful tools to provide a wide range of benefits to the farm system and wider environment, while at the same time helping to reduce reliance on agrichemicals and nitrogen fertiliser. They are therefore key tools in facilitating the transition to agroecology (FAO, 2023).

7. Further resources and information

A review of leguminous fertility-building crops, with particular reference to nitrogen fixation and utilisation 2003 https://www.organicresearchcentre.com/manage/authincludes/article_uploads/iota/technical-leaflets/a-review-of-leguminous-fertility-building-crops.pdf

Agricology: Cover Crops https://agricology.co.uk/resource/cover-crops/

Benefits and risks of intercropping for crop resilience and pest management 2022 Huss Holmes Blubaugh doi:10.1093/jee/toac045 https://academic.oup.com/jee/advance-article/doi/10.1093/jee/toac045/6572575

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DIVERSify: Designing InnoVative plant teams for Ecosystem Resilience and agricultural Sustainability https://plant-teams.org/

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Guidelines for Intercropping 2009 Mohler Stoner https://www.sare.org/resources/crop-rotation-on-organic-farms/

Intercropping—Evaluating the advantages to broadacre systems 2021 Khanal Stott et al doi:10.3390/agriculture11050453 https://www.mdpi.com/2077-0472/11/5/453

Managing cover crops profitably 3rd ed 2007 SARE https://www.sare.org/resources/managing-cover-crops-profitably-3rd-edition/

Organic Farm Knowledge: Cover crop and living mulch toolbox https://organic-farmknowledge.org/tool/30563

ReMix - Redesigning European cropping systems based on species mixtures https://www.remix-intercrops.eu/

SARE Cover Crops https://www.sare.org/sare-category/crop-production/cropping-systems/cover-crops/

The ecology of intercropping 1992 Vandermeer https://www.cambridge.org/core/books/ecology-of-intercropping/ACD6773C1D43F28D8B499F5D36A649D1

The potential for companion cropping and intercropping on UK arable farms 2016 Howard http://nuffieldinternational.org/live/Report/UK/2015/andrew-howard

UC Davis Cover Crops Database https://sarep.ucdavis.edu/covercrop

8. Glossary

Arthropod - invertebrate animals that have an exoskeleton - commonly called 'insects'.

Beneficial insects - arthropods that provide benefits to agroecosystems (farm systems). This includes natural enemies as well as other arthropods, e.g., pollinators.

Economic threshold - the population of an arthropod pest, pathogen or weed below which the cost of control is higher than the financial return. In IPM systems when a pest, pathogen or weed is below its economic threshold no control action is taken. Undertaking control measures below an economic threshold is economically irrational.

Ecosystem services - are the benefits provided to humans by the natural environment and ecosystems.

Integrated Pest Management (IPM) - is a sustainable approach to managing pests by combining biological, cultural, physical, and chemical tools in a way that minimizes economic, health, and environmental risks.

Natural enemies - arthropods that attack crop pests.

Nitrogen robbery - where crop residues that have a high carbon content, cause soil microbes to use up available soil nitrogen, as they decompose the residue, creating temporary soil and thus plant nitrogen deficiency.

Parasitic wasp - see parasitoid.

Parasitised - the process by which a parasitoid lays an egg on or in its host.

Parasitoid - an insect, typically a wasp, whose larvae feed and develop within or on the body of other arthropods eventually killing it and is free-living as an adult.

Rectangularity - is the spatial distribution of individual plants in crops sown in rows. It is the ratio of the mean distance between rows and the distance between individual plants within a row, i.e., if plants are on the corners of a square or rectangle. Increasing rectangularity tends to increase competition among crop plants and reduce yields.

RTK-GPS - Real-time kinematic - global positioning system: the most accurate form of GPS guidance and steering systems for tractors and other farm equipment, e.g., robots.

Weed seedbank - the 'bank' of weed seeds in the soil from which future infestations of weeds originate.

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