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A review of the benefits, optimal crop management practices and knowledge gaps associated with different cover crop species

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CONTENTS

1. Abstract

Cover crops are grown primarily for the purpose of 'protecting or improving' between periods of regular crop production. There are four main types of use including; improving soil fertility, improving soil structure, managing weeds and pests and environmental management. The most appropriate cover crop species/management will depend on what the grower wants to achieve from the cover crop. Direct financial benefits can be assessed most easily though improvements in yield of following crops. However, sometimes yield improvements may be detected later in the rotation and repeated cycles of cover crop use may be required. Beyond yield improvement, cover crops can provide additional benefits for the farm and the environment (e.g. reduced soil erosion risk). However, there are also potential undesirable effects (e.g. rotational conflicts, increased weed issues and increased costs). This review investigates the scientific basis of the reported functions of cover crops to better understand the feasibility of these benefits including; nitrogen (N) fixation, uptake and release; weed suppression by allelopathic effects and physical competition; biofumigation against pests; soil erosion and runoff; soil health and fertility, including soil organic matter, soil physical properties and soil biology; cover crops as forage; biodiversity and habitat provision. Cover crop agronomy is reviewed including; common cover crop choices, establishment methods, starter fertiliser, pest management and cover crop destruction. Economic and decision making factors, including yield and economic responses are reviewed and methods for evaluating cover crops on farm given.

Some of the key conclusions include; the most important agronomic factor for achieving benefits for cover crops is to establish early (late summer/early autumn); N uptake during autumn/winter is typically 30-100 kg N ha^{-1}, with 10-100 kg N ha^{-1} released to the following crop; N fixation is most effective between 7°C and 20°C which means little N is usually fixed over-winter; a canopy cover of 30% or more over winter decreases risk of soil erosion and run off; increases in soil organic matter following cover crops ranged from zero up to 42%, with no study reporting a decline; cover crops with allelopathic effects include several cereal and brassica species, buckwheat, clovers, sorghum, hairy vetch, sunflower and fescues.

Knowledge gaps include the characterisation and performance evaluation of different cover crop types, species and varieties, particularly under different conditions (e.g. soil type and weather). The effects of cover crops will be best understood using a network of long-term coordinated farm-scale experiments which feature common treatments and assessments. This will be particularly important for evaluating effects on soil organic matter which changes slowly over many years. A continually updated database is required to support decision making, calculate cost benefits and to focus research. Other priority knowledge gaps include characterisation of rooting, uptake and release of N and other nutrients, impacts on weeds, disease & pests in following crops, effects of livestock grazing and most appropriate techniques for cover destruction and establishment of the following crop.

2. Cover Crops Potential Advantages and Disadvantages

Cover crops have previously been defined as crops grown to protect the soil from erosion and losses of nutrients via leaching and runoff (Reeves 1994). In the Encyclopaedia of soil sciences (Delgado et al. 2006) the definition was expanded to *crops which are grown for improving soil, air and water conservation and quality; nutrient scavenging, cycling and management; increasing populations of beneficial insects in integrated pest management; and for short-term animal cropping grazing systems* (Delgado et al. 2007; Delgado et al. 2006). This can essentially be condensed into crops which are grown primarily for the purpose of 'protecting or improving' between periods of regular crop production (Anon 2015). Reeves (1994) described cover crops as short-term rotations, Cover crops are grown between the harvest and establishment of main (cash) crops. The terms cover crop, catch crop and green manure are sometimes used interchangeably but they can also be used more specifically to distinguish between different functions. A catch crop is a crop which is grown to 'catch' the available N in the soil and prevent nutrient losses via run-off and leaching (Thorup-Kristensen et al. 2003; Anon 2015). A green manure is grown to improve nutrition for the following crop, through addition of fresh biomass (organic matter) and nutrients to the soil (Anon 2015). Additionally, in the greening rules as part of the basic payment scheme (BPS) there are minimum establishment dates and growth periods: As part of the ecological focus areas (EFA) rules catch crops must be established by the 31st August and retained until at least 1st October in the same year. Cover crops must be established by 1st October and retained until at least the 15th January in the following year (Anon 2016).

There are both disadvantages and advantages to cover crops, the majority of which are listed in Table 1 and Table 2. Cover crops can provide benefits across the rotation, but direct financial benefits can be assessed most easily though improvements in yield in the following crops (Stobart 2015). It should be noted that sometimes yield improvements will not be detected in the crop immediately following the cover crop, but may be detected later in the rotation and that repeated cycles of cover crop use may be required to fully exploit the potential benefits (Stobart 2015). Yield responses in the crop following the cover crop will vary depending on the cover crop, following crop, environmental and site conditions and management (Stobart 2015). Beyond yield improvement, cover crops can provide additional benefits for the farm system and the environment (e.g. reduced soil erosion risk, improved surface drainage, increased soil organic matter (SOM)). However, there are also potential undesirable effects from using cover crops in the rotation (e.g. increased pest and disease, rotational conflicts, increased weed issues and increased costs).

Cover crops are frequently grouped into one of two groups: either legumes and non-legumes which includes grasses and brassicas (Clark 2012) (although the latter may be treated as a third group (Anon 2015; Stobart 2015)); or as cereals and non-cereals, as they are in the common agricultural policy (CAP) rules (Anon 2016). Legume cover crops convert nitrogen gas in the atmosphere into soil nitrogen. Legume cover crops can also be used to improve soil structure (Clark 2012). Common legume cover crops are vetches, clovers, black medick (yellow trefoil), peas and beans. Legume cover crops can also be used to reduce erosion, produce biomass, add organic matter to the soil and attract beneficial insects (Clark 2012). Rotational intensity should be considered when other legumes and pulses are grown in the rotation, to prevent disease carry over (Stobart 2015). Non-legume crops are most useful for scavenging nutrients, reducing erosion, producing large amounts of plant residue, adding organic matter to the soil and suppressing weeds (Clark 2012). Graminacious species (grasses) usually provide rapid ground cover when sown in the autumn (Stobart 2015). Grasses are considered to be good at scavenging excess nutrients, especially N, left in the soil after harvest (Clark 2012). Grasses also tend to root at a shallower depth compared to other cover crop types such as brassicas, however this shallow rooting may be beneficial for opening up the surface soil (Stobart 2015).Typical grasses include rye, oats and sorghum-sudangrass. Brassicas, such as mustards and radishes, are also used as cover crops and these may have biofumigation properties. Brassicas can be competitive with rapid quick growth and develop strong root systems which have been shown to improve soil structure (Clark 2012; Stobart 2015; Chen and Weil 2009; Williams and Weil 2004). Brassicas are also thought to help reduce nitrate leaching and soil erosion. Rotational intensity should be considered, as they can have an impact on disease carry over, volunteers and weed issues (Stobart 2015).Other non-legume cover crops which are not grasses or brassicas include but are not limited to Phacelia (Boraginaceae), buckwheat (Polygonaceae) and chicory (Asteraceae).

Mixtures of two or more cover crops are common and can be more effective than a single (or straight) species. It should also be noted that in the EFA rules catch and cover crops must be made up of at least two cover crop types, at least one cereal and one non-cereal, that establish quickly, achieve ground cover and will use available nutrients (Anon 2016). Mixtures of cover crops offer multiple benefits, combining the properties of the different component species to fit a specific set of needs. There are cases where the mix of species work together to give an additional benefit, e.g. mixing a grass and a legume may enhance N fixation (see section 3.1.1.). Mixtures can also provide some risk management offering stability of performance (Döring et al. 2013), in response to different environmental conditions and soil types. For example, if one species in the mix has poor establishment then other species components may be able to compensate for this. Some disadvantages of mixtures include: higher cost of seed, too much plant residue, or more complicated management (Clark 2012).

Table 1 Potential advantages of cover crop use, with key references in which these are discussed. For some of these effects there is general consensus in the literature, ✓, and for some of these effects findings are limited or have only been reported in specific circumstances, ○.

Advantages/Desired Effects		**References**
Cover crops can be managed and used as trap crops to break pest life cycles and reduce pest populations (e.g. nematodes) in the main crop.	✓	(Rayns and Rosenfeld 2006; Snapp et al. 2005; Clark 2012)
Increase populations of beneficial insects and parasitoids which can reduce insect damage	○	(Dabney et al. 2001; Clark 2012)
Weed suppression through either competition for resources from the growing crop, cover crop residue blocking light or allelopathic effects.	○	(Ramírez-García et al. 2015; Haramoto and Gallandt 2004; Hartwig and Ammon 2002; Reeves 1994; Clark 2012).
Reduced N leaching (at high leaching intensities)	✓	(Thorup-Kristensen et al. 2003; Meisinger et al. 1991; Delgado et al. 2007; Reeves 1994; Snapp et al. 2005)
Reduced nitrate concentrations in the soil system at low leaching intensities	○	(Thorup-Kristensen et al. 2003)
Increased availability of nutrients. Cover crops can mobilize, take up and mineralize nutrients, preventing them from leaching or being fixed in the soil and increase their availability for the following crop. Additionally, legume cover crops can fix N from the atmosphere	✓	(Eriksen and Thorup-Kristensen 2001; Hartwig and Ammon 2002; Snapp et al. 2005; Clark 2012)

Improved soil fertility, physical conditions and structure, improved tilth, increased soil organic matter, increased base N mineralization, and enhance soil microorganism activity.	✓	(Thorup-Kristensen et al. 2003; Haramoto and Gallandt 2004; Dabney et al. 2001; Hartwig and Ammon 2002; Reeves 1994; Snapp et al. 2005; Clark 2012)
Reduce soil erosion	✓	(Haramoto and Gallandt 2004; Thorup-Kristensen et al. 2003; Dabney et al. 2001; Hartwig and Ammon 2002; Reeves 1994; Snapp et al. 2005; Clark 2012)
Protect water quality	✓	(Clark 2012; Dabney et al. 2001)
Improved crop rooting depth	○	(Thorup-Kristensen et al. 2003)
Loosen subsoil	○	(Hamza and Anderson 2005)
Increase water infiltration into soil	✓	(Dabney et al. 2001; Stobart and Morris 2011; Reeves 1994; Clark 2012)
Conserve soil moisture in some circumstances. Residue can increase water infiltration and reduce evaporation losses	○	(Clark 2012)
Increased yields	○	(Stobart 2015; Clark 2012; Dabney et al. 2001; Delgado et al. 2007; Hartwig and Ammon 2002)

Table 2 Potential disadvantages of cover crop use, with key references in which these are discussed. For some of these effects there is general consensus in the literature, ✓, and for some of these effects findings are limited or have only been reported in specific circumstances, ○.

Disadvantages/Undesired effects		References
Increased pest & disease pressure. The cover crops can act as a host for pests and pathogens. Providing a ‘green bridge’ between main crops.	✓	(Rayns and Rosenfeld 2006; Thorup-Kristensen et al. 2003; Snapp et al. 2005).
Increased slug populations as a result of grass cover crops have been reported in some situations.	○	(Anon 2002; Frank 1998)
Increased weed pressure either through issues with rotational weed management or the cover crop becomes a weed in subsequent rotations	○	(Rayns and Rosenfeld 2006; Thorup-Kristensen et al. 2003)
Allelopathic effects may have a negative effect on the main crop	○	(Dabney et al. 2001; Reeves 1994)
Increased N fertilizer requirement due to use of plant available N (known as pre-emptive competition) by the cover crop, or immobilization of N during cover crop decomposition	○	(Thorup-Kristensen et al. 2003; Snapp et al. 2005)
Reduce soil moisture in other circumstances. Transpirational losses of soil water by cover crops can negatively impact on cash crops	○	(Dabney et al. 2001; Reeves 1994)
Loss of cash crop when undersowing green manures, as the cover crop may compete for resources.	○	(Thorup-Kristensen et al. 2003; Känkänen and Eriksson 2007)
Additional costs of seed, additional cultivations and crop management	✓	(Rayns and Rosenfeld 2006; Dabney et al. 2001; Reeves 1994; Snapp et al. 2005)
Additional work at busy times of the year	✓	(Rayns and Rosenfeld 2006; Dabney et al. 2001)

3. Scientific Theory behind Cover Crops

3.1. Nitrogen uptake and release

3.1.1. The process of nitrogen fixation

Legume based cover crops can supply additional N through biological nitrogen fixation (BNF) from the atmosphere (Askegaard and Eriksen 2008; Amosse et al. 2014). Most legume species are able to form a symbiosis with alpha- or beta- proteobacteria, collectively called rhizobia (Baddeley et al. 2014). Root nodules are the primary site of BNF in legumes. This review will not describe the mechanism of nodulation in detail, as this has been described elsewhere (for example: Andrews et al. 2009; Oldroyd and Downie 2004). However, briefly, nodulation begins with the recognition of host plant-induced rhizobial nod factors by receptors in root epidermal cells. This triggers calcium oscillations, membrane depolarisation and signal cascades that lead to root hair curling and root cell wall degradation at the site of infection (Gonzalez-Guerrero et al. 2014). The rhizobia form an infection thread into the epidermal cell, which eventually releases the rhizobia into the primordial nodule cells. After a period of division nitrogen-fixing bacteroids are formed (Gonzalez-Guerrero et al. 2014). There is a delay between germination and the production of fully functional nodules, during this time the crop is reliant on seed reserves and soil N (Andrews et al. 2009). Infection of the root hairs can occur as early as four days after germination, and the infection develops into visible nodules three to five weeks after emergence depending on the crop species and environmental conditions (Hannaway et al. 1982; Understander et al. 2011).

There are a number of leguminous cover crops available, and this section of the review will focus on estimating how much nitrogen a leguminous cover crop can fix and the factors that can affect nitrogen gas (N_2) fixation. It is important that sufficient rhizobia bacteria are present in the soil to give good root nodule formation, and hence N_2 fixation. The N fixed by the cover crop becomes available to the following cash crop after the cover crop is incorporated into the soil and the plant residues mineralise. Nitrogen fixation and the residual effects of the cover crop on the following crop are variable and affected by a number of factors including species, soil type, local climate and management (Sparrow et al. 1995; Carlsson and Huss-Danell 2003; Doltra and Olesen 2013; Li et al. 2015).

It has been estimated that the process of N_2 fixation requires approximately 22.8 g glucose per g of N_2 reduced, which is divided between the direct energetic cost of N_2 fixation and the costs of construction and maintenance of the nodules (Gustschick 1981); cited in (Thomas et al. 2006). It is challenging to determine the carbohydrate costs of symbiosis under field conditions, but it has been estimated that 25-33% of the carbon fixed in photosynthesis is used by N_2 fixing bacteria in nodules (Pate 1986; Lambers et al. 1998) cited in (Thomas et al. 2006).

It is difficult to quantify N_2 fixation for several reasons, including that there are several different methods of doing so, which each have their merits and drawbacks. The different methods used can often make comparing data difficult (Cuttle et al. 2003). Additionally, It is important to also consider the amount of N contained in the roots in order to accurately estimate the total N which can be added to the system (Buchi et al. 2015). It has been estimated that the roots may contribute from between 20-60% of above ground N (Cuttle et al. 2003). A correction factor of 1.65 has been suggested for white clover, to account for the amount of N in both the roots and stubble when N_2 fixation is estimated by harvesting the leaves only (Jorgensen and Ledgard 1997). Rhizodeposition is also an important process which adds N to the soil and is also difficult to quantify (Fustec et al. 2010). Nitrogen deposition values ranging from 4-71% of total plant N were reported by Fustec et al. (2010). Others have suggested that BNF was underestimated by 19-25% when only the harvested material was measured (Hogh-Jensen and Kristensen 1995). Another potential issue when quantifying the amount of N_2 fixed is the risk of double counting due to the complex nature of N cycling (Cuttle et al. 2003). In 1992 Cuttle *et al.*, concluded that information on N fixation capacity and yield under UK conditions is limited for the more minor legume crops (e.g. subterranean clover (*Trifolium subterraneum)*, Persian clover (*T. resupinatum*), Trefoil or black medic (*Medicago lupulina*) and Sainfoin (*Onobrychis viciifolia*). The most commonly grown legumes for fertility building under UK conditions are white clover, red clover, lucerne, vetch and peas and beans.

Different legume species and cultivars vary in their ability to fix N_2, ranging from 15 to 325 kg N ha^{-1} yr^{-1}, and environmental and management factors heavily influence rates of N_2 fixation (Hardarson and Atkins 2003; Hardarson et al. 1987). The percentage of plant N supplied from N_2 fixation is averaged at 50-60% in grain legumes, but is as high as 70-80% in forage legumes (Danso 1995). Most published estimates of N_2 fixation relate to annual rates, however knowledge of relative rates of fixation at different growth stages and in different seasons will be important for legumes grown for less than a year (Cuttle et al. 2003). The quantity of N fixed by relatively short-duration cover crops will be influenced by how rapidly the crop establishes and develops an effective rhizobial symbiosis (Cuttle et al. 2003). In Denmark the average rate of N_2 fixation of a white clover and perennial ryegrass mixture varied from less than 0.5 kg N ha^{-1} day^{-1} in autumn to more than 2.6 kg ha^{-1} day^{-1} in June (Jorgensen et al. 1999). While in Scotland, a white clover sward was observed to have little N fixation activity in March, but that activity increased when the top 10cm soil temperatures exceeded 3°C (Marriott 1988). In a field experiment in Nebraska the growth of 20 species were compared based on planting date and length of growing period (Power and Koerner 1994). All species were planted in the spring and reseeded in the summer

(June – July). In most situations hairy vetch performed well and small seeded legumes exhibited slow growth for the first 60 days. Power and Koerner (1994) suggest that certain large seeded, cool season legumes would be best for early sowing. These authors concluded that hairy vetch appears to have a wide range of adaptability (Power and Koerner 1994).

In situ ^{15}N labelling is considered a suitable approach to quantitatively study biological nitrogen fixation in legumes, to estimate the below ground N and to trace the fate of N in rotations (Mueller and Thorup-Kristensen 2001; Carlsson and Huss-Danell 2003; Li et al. 2015). Li et al., (2015) found, in a field study in Denmark, that in three legume based cover crops, which were either undersown in the preceding crop (May) or sown the day after harvest (August) according to normal practice, more than 60% of the N in the tops and 31 – 46 % of N in the roots was derived from the atmosphere by late autumn (October) when they were harvested (Li et al. 2015).

Table 3 gives examples from the literature of the amounts of N fixed by a range of cover crop species. A field study in Switzerland assessed the biomass production, N content and the amount of N derived from BNF of 19 legumes and two non-legumes to assess their potential use as cover crops in the context of a four month (August to November) growing period (Buchi et al. 2015). In the study some species were able to fix more than 100 kg N ha^{-1} in the three month growing period. Notably, *V. faba* fixed 150 kg N ha^{-1} and substantial amounts of N were accumulated by hairy vetch and common vetch. When accounting for the seed cost per hectare, hairy vetch and common vetch were recommended for the two locations (Buchi et al. 2015).

The field study of Li *et al*., (2015) indicated an average N fixation rate of 24 kg N per dry matter tonne of above ground tissues for red clover, winter vetch and a perennial ryegrass-red clover mixture. Another study reported N fixation rates of 23 kg N fixed t^{-1} for red clover in northern temperate regions (Carlsson and Huss-Danell 2003). Interestingly, Li *et al*., (2015) observed a slightly higher percentage of N derived from the atmosphere in the grass clover mix (59%) compared to the straight red clover (55%), which supports the findings of other studies (Carlsson and Huss-Danell 2003; Rasmussen et al. 2012), that mixes of legumes and grasses can increase BNF. This may be due to competition for soil N from the companion grass stimulating increased N fixation by the legume (Rasmussen et al. 2012). Li *et al*., (2015) also found that the amount of N fixation was positively correlated with dry matter production. Other studies have also reported a strong relationship between the amount of N fixed and shoot dry matter (Evans et al. 1989). Global biological N fixation was estimated at 15-25 kg shoot N for every tonne (or mega gram (Mg)) shoot dry matter accumulated (Herridge et al. 2008). These figures allow an estimation on N fixation from biomass production (Li et al. 2015).

Table 3 The amounts of nitrogen fixed by different species. Other relevant information is given along with the reference source.

Species	Range of N fixed	Other information	Reference
Red clover *(Trifolium pretense)*	8 – 177 kg N ha^{-1}	In the sowing year (between spring and winter crops in the same year) of several studies in Northern Temperate regions.	(Li et al. 2015; Carlsson and Huss-Danell 2003)
Crimson clover (*Trifolium incarnatum*)	77 - 111 kg N ha^{-1}	Growing period July/August to November in Denmark, the study was conducted over two years	(Mueller and Thorup-Kristensen 2001).
Persian clover (*T. resupinatum*)	100 kg N ha^{-1}		
Egyptian or Berseem clover (*T. alexandrinum*)	32 – 69 kg N ha^{-11}		
Common vetch (*Vicia sativia*)	40 – 90 kg N ha^{-1}		
Hairy or winter vetch *(Vicia villosa)*	149 kg N ha^{-1}		
	75 – 80 kg N ha^{-1}	When an autumn sown winter cover crop was killed in the spring, grown in Georgia, USA	(Nesmith and McCracken 1994).
Lucerne or alfalfa (*Medicago sativa*)	36 kg N ha^{-1}	After 12 weeks growth, sown in the spring in Canada.	(Townley-Smith et al. 1993).
Field or broad bean (*V. faba*)	150 kg N ha^{-1}	Three month growing period (August to November) in Switzerland	(Buchi et al. 2015).

Factors that limit plant growth normally also limit N_2 fixation, either through directly affecting nodule formation and function or by limiting nutrient supply by the host plant (Cuttle et al. 2003). Some forms of stress such as drought, waterlogging and extreme temperatures, can have a greater effect on nodule function than nitrate uptake (Cuttle et al. 2003). Fixation can also be affected by soil structure and disease (Cuttle et al. 2003). It has been reported that legumes will only fix nitrogen when the soil is above 8°C (Rosenfield and Raynes 2011). Early studies demonstrated that low temperatures generally inhibit root hair infection more than nodule initiation, development or N assimilation (Cuttle et al. 2003). The effects of temperature differ between species and cultivars within a species. In a glasshouse experiment, at 10°C total N uptake and fixation was greatest for hairy vetch and faba bean. While at 20°C faba bean and soybean had high growth and N uptake while field pea and crimson clover did not perform well. (Power and Zachariassen 1993; Zachariassen and Power 1991). In another glasshouse study narrow leaved lupin was grown at 7, 12 and 25°C (Peltzer et al. 2002). Low temperatures were found to inhibit nodulation and there appeared to be a critical temperature of between 7 and 12°C, below which nodulation did not occur. In Finland, lucerne and red clover nodules were found to remain active down to 1.5°C soil temperature (0.5°C air temperature), although the activity was 2-4% of the seasonal maximum (Lindstrom 1984). There is also evidence that nodules may survive at lower temperatures. White clover and *Trifolium ambiguum* were planted in the Snowy Mountains in Australia and nodules were present on the over wintering plants in the spring, Although the nodules were shrivelled, the survival of the vascular system of the nodule enabled N fixing tissue to be formed at least two weeks before new nodules could develop (Bergersen et al. 1963). The origin of the rhizobial component will also affect the sensitivity of N fixation to temperature (Cuttle et al. 2003). High temperatures can also inhibit N_2 fixation, with maximum activity of temperate species occurring between 20 and 30°C (Cuttle et al. 2003).

Over winter temperatures (November to February) in the UK can vary from mean daily maximum temperatures of >8°C in the south to mean daily minimum temperatures of <-4°C in the north (Met office averages from 1981 – 2010). The mean daily temperatures for six months from October to March are shown in Figure 1, these demonstrate that much of the UK has an average temperature of below 8°C in November, and below 6°C from December through to March. Therefore the relatively low UK temperatures during these months will inhibit nodule formation and reduce N fixation (compared to that which would be expected at other times of year for a given legume / cover crop). This will ultimately limit the amount of N which is fixed by a leguminous cover crop during winter and increases the importance of establishment during late summer or early autumn when conditions are warm. The high carbon cost of N fixation also means that low levels of N fixation will be expected over-winter when photosynthesis is low due to low levels of radiation.

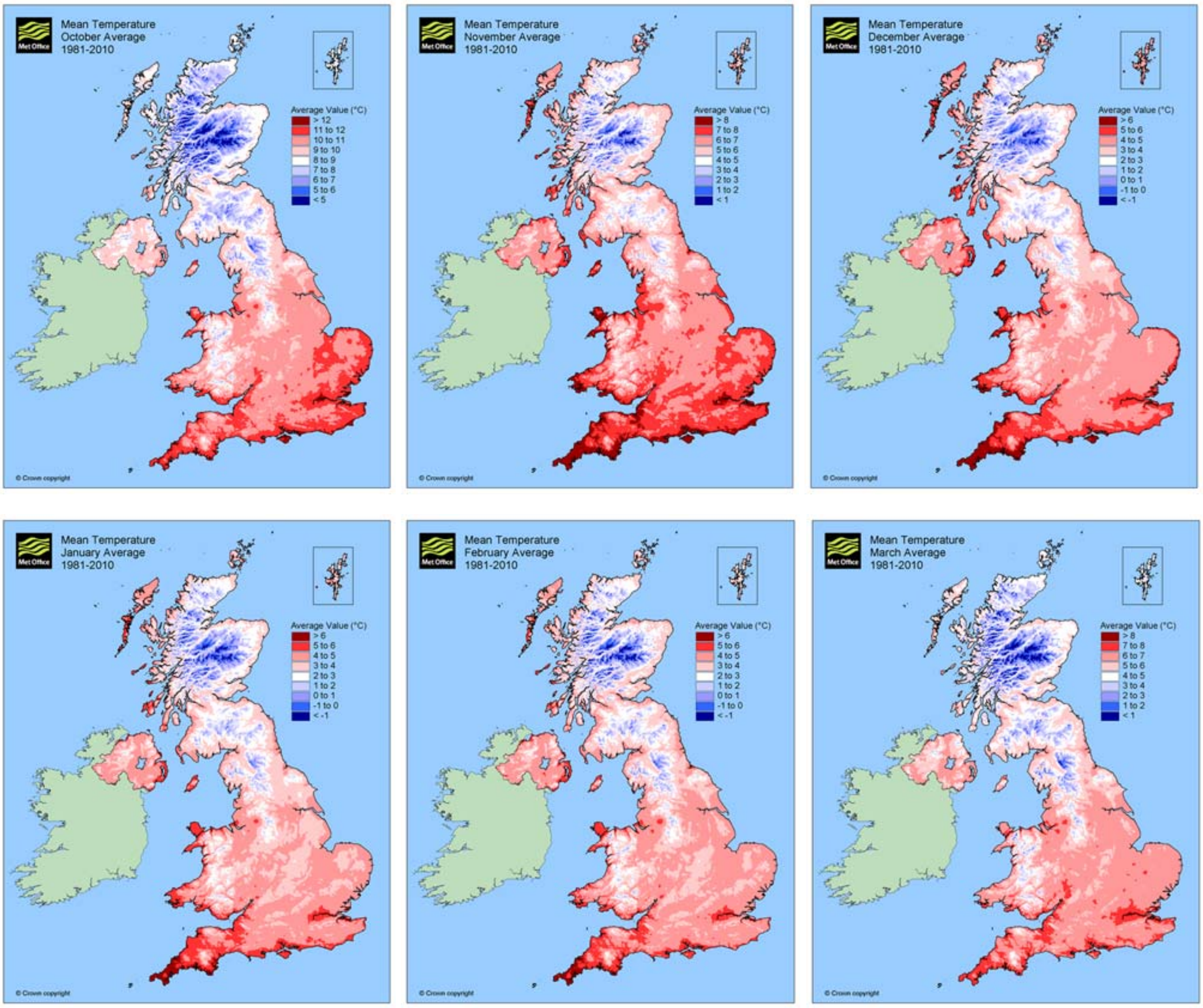

Figure 1 Mean UK temperature in the six months between October and March, averaging period 1981 – 2010. Please note the changing scale in these maps.

The growth of legumes in a mixed crop can affect fixation in opposing ways. The companion crops will reduce the population of legume plants and may compete for nutrients, water and light. On the other hand, the companion crop may reduce the availability of soil N and encourage the legume to fix a greater proportion of N from the atmosphere, as mentioned above (Cuttle et al. 2003). An increased availability of mineral N in the soil has a negative effect on N_2 fixation (Cuttle et al. 2003). In general, legumes will obtain less of their N from the atmosphere if there is adequate soil available N (Cuttle et al. 2003). Therefore more N is likely to be fixed when legumes follow crops that have depleted the soil N. It has been reported that, due to their ability to fix N, legumes are less effective in extracting soil N compared to non-legumes (Thorup-Kristensen et al. 2003; Bergkvist et al. 2011) which may lead to higher risks of nitrate leaching or denitrification (Li et al. 2015). A review of eleven studies (Meisinger et al. 1991) reported that the average reduction of N leaching by different types of cover crops was 61% (range of 31-77%) for grasses, 62% (range of 35-87%) for brassicas and 25% (range of 6-45%) for legumes. The legume futures report (Baddeley et al. 2014) states that the residues of legume crops are just as likely to contribute to nitrate leaching or to N_2O release as other crop residues but that a proportion of the fixed N remains in the agricultural system, reducing N fertiliser needs in subsequent crops.

Main Points:

- Visible nodules develop three to five weeks after crop emergence depending on the legume species and environmental conditions.
- Different legume species and cultivars vary in their ability to fix N, ranging from 15 to 325 kg N ha^{-1} yr^{-1}. Rates of fixation are influenced by environmental and management factors.
- N fixation between late summer and winter was generally between 30 and 100 kg N ha^{-1}, but could be as much as 150 kg N ha^{-1}
- N fixation is positively correlated with dry matter production. Global biological N fixation is estimated at 15-25 kg shoot N Mg shoot DM^{-1}.
- The effects of temperature on N fixation varies between species and cultivars within a species. Reported temperature range for N fixation is 1.5°C to 30°C. With the most active range of N fixation occurring when soil temperatures are between 7°C and 20°C.
- It has been estimated that 25 – 33% of the carbon fixed in photosynthesis is used by N_2 fixing bacteria in nodules, which is considered a high carbon cost.
- Mixes of legumes & non legumes can encourage greater N fixation and lower N leaching risk than a sole legume cover crop.

3.1.2. Nitrogen uptake

Over winter cover crops are commonly used to take up and hold nutrients, including nitrogen (N), on what would otherwise be bare or stubbled ground and help prevent over winter leaching. The amount of N taken up by over winter cover crops is affected by species and biomass achieved. Table 4 summarises the typical amount of N taken up over winter for a range of species. Harrison (1998) found that over winter cover crops (winter rye, barley, forage rape, white mustard, stubble turnips, phacelia) drilled in August-October and destroyed in December-March on a variety of UK soil types on average took up a maximum of 30 kg/ha N. Cover crop above ground biomass was for most trials proportional to total N uptake in this study. Ranells and Wagner (1996) recorded a spring N content of 154 kg N/ha for a straight hairy vetch over winter cover crop, and 41 kg N/ha content in spring for an over winter rye cover crop in Carolina, USA. In Canada on a silty clay loam, crimson clover and cereal cover crops were established in August-September. Rye crops were found to take up 61 kg N/ha, whereas crimson clover grown for the same period took up 28 kg N/ha which was significantly less than the rye crop (Odhiambo *et al.* 2008). In rye cover crops grown in Iowa USA between September and May in soybean and maize rotations, a N content of approximately 30 kg N/ha was measured just before cover crop destruction (Patoja et al, 2016). Brassica cover crops have been documented to take up 100-120 kg N/ha over winter. In the NE USA, late August planted white mustard (*Brassica hirta* Moench) took up 116 kg N/ha and oilseed radish (*Raphanus sativus*) 127 kg N/ha before the crops were killed naturally by cold temperatures and frost in December (Stivers-Young, 1998). Dean and Weil (2009) found that oilseed radish sown in August, in the mid-Atlantic USA on sandy soils in a no tillage system, and destroyed by frost in December was able to take up an average of 120 kg N, with around 80% of that N contained in the shoots and 20% in the roots.

Main points

- Uptake of N by cover crops sown in late summer/autumn ranges from 30 to 120 kg N/ha before spring.

3.1.3. Nitrogen release

After growth and incorporation of the cover crop over autumn and winter, the N either fixed or captured by the cover crop has to be broken down to become available for the following cash crop. How soon nitrogen becomes available to following crops, due to the process of mineralisation, will depend on many factors (Jarvis et al. 1996). High rates of mineralisation occur when the soil is warm and moist (Rayns and Rosenfeld 2006). Besides climatic conditions, the carbon to nitrogen (C:N) ratio of the residues is the main factor influencing the dynamics of mineralisation of the nitrogen accumulated by the cover crops and consequently its availability for the succeeding crop and the risk of nitrate leaching (Thorup-Kristensen and Nielsen 1998; Justes et al. 2009). Additionally, the decomposition of crop residues is affected by lignin, cellulose and polyphenol content (Fillery 2001; Wichern et al. 2008).

The residual effect of cover crops on N supply in the rotation is determined mainly by the soil N depletion by the cover crop (pre-emptive competition; (Thorup-Kristensen et al. 2003)) and the balance of subsequent mineralisation and immobilisation during decomposition of residues (Thorup-Kristensen et al. 2003). Under some conditions, mineralization from the cover crop cannot compensate for the effect of N uptake by the cover crop, which reduces N supply for the succeeding crop and is termed pre-emptive competition (Thorup-Kristensen et al. 2003). The harvest and removal of cover crop tops, may exacerbate this negative impact (Li et al. 2015). In cases of strong pre-emptive competition, where cover crops deplete the majority of mineral N from the soil, they can have a depressive effect on N supply for the following crop (Thorup-Kristensen et al. 2003; Thorup-Kristensen and Nielsen 1998). A field study in Slovenia found that a pure Italian ryegrass cover crop, or crimson clover and Italian ryegrass mixtures with high proportions of Italian ryegrass without starter N, had a depressive effect on the whole above

ground DM, grain yield and N content of the following maize crop (Kramberger et al. 2014). In contrast, over winter cover crop mixtures of crimson clover and Italian ryegrass with higher proportions of crimson clover gave higher maize yields and N contents than cover crop mixtures with high proportions of Italian ryegrass (Kramberger et al. 2014).
Previous research in the UK has shown that cover crop type, growth, environmental conditions and location all have a bearing on N uptake and release and that the amounts and timing of release can be highly variable (e.g. Döring et al. (2013)) More recent work investigating cover crop performance and yield response following a cover crop (Stobart and Morris 2014; Shah et al. 2015) have tended not to separate N release from other potential drivers (e.g changes to soil structure). It has been reported that cover crops have their biggest effect on soil mineral nitrogen within the first year after incorporation (Rayns and Rosenfeld 2006). Table 4 summarises the typical amount of N released for the following crop after the cover crop for a range of species. Work on over winter cover crops of oil radish, winter rye, white mustard and oilseed rape grown before potatoes has shown that 15-50 kg N/ha is recovered by the potato crop when cover crops are destroyed before the end of February (Silgram *et al.* 2015). It was noted that the amounts and timings of release were variable as was the net economic impact of the cover crop on the following crop.

Over winter cover crops (winter rye, barley, forage rape, white mustard, stubble turnips, phacelia) were drilled August-October and destroyed in December- March on a variety of soil types in the UK by Harrison (1998). It was found that most mineralisation of N in cover crop residues into forms usable to the following crop occurred eight weeks post incorporation of the cover crop, by ploughing to 20 cm depth. Three months after cover crop incorporation, 25-33% of total cover crop N was estimated to have mineralised at a loamy sand site according to a soil core incubation method. N uptake by the following crop was significantly higher after cover cropping on a loamy sand but not a flinty sandy loam overlying chalk. In a following UK study, Harrison (1999) averaged four years of trials on a loamy sand site, and found an estimated 17% of the N contained in a winter barley cover crop was used by the following spring cereal crop. Utilisation of cover crop N by the following spring crop was estimated by correlation of cover crop N supply and following crop grain and straw N offtake. In these trials cover crop material was grown over autumn and winter at a separate site, then as far as possible above and below ground material was transported to the trial plots where it was incorporated to 20 cm depth each March before a spring barley test crop, for two years. The method of transporting cover crop material from one field to another, which is not practical for UK farms growing cover crops, was used as this study was investigating total N mineralisation from cover crop residue when incorporated and this would have been complicated with cover crop N uptake if cover crops were grown at the site of incorporation. Plots with cover crop addition in the first year but not in the second showed higher following crop N offtake than plots which had received no cover crop incorporation in either years 1 or 2, indicating a carry-over of additional N which could be available for at least the two seasons following cover cropping. In the same trials on a silty clay loam site, an estimated 11% of a cereal cover crop N was taken up by the following spring cereal crop. The C:N ratio of cover crop material was measured each year and it was found that lower ratios (e.g. 12.9) correlated strongly with increased N offtake of the following crop and therefore N mineralisation at the loamy sand site. On the silty clay loam site there was less correlation between the cover crop C:N ratio and following crop N offtake. However, in general it has been found that release of N contained in cover crop residues occurs more readily in residues with a lower cover crop C:N ratio (Clark 2012; Mary et al. 1996).

Cover crop residue C:N ratio and therefore potential mineralisation rate varies with species. Leguminous cover crops have a lower C:N ratio (e.g. hairy vetch 11) than brassica species (roots C:N ratio 20- 30, shoots C:N ratio 10-20), and cereal cover crops have higher C:N ratios than both of these species (e.g. mature rye straw 82; Clark, 2012; Table 4). Tribouillois et al. (2015) found by using both field experiments in France and soil-crop modelling that an over winter cover crop mixture containing a legume and a non-legume species resulted in higher amounts of N mineralisation in the following crop than with an over winter non-legume cover crop species grown alone. In North Carolina, USA, Ranells and Wagger (1996) placed residues of over winter grown rye, vetch and crimson clover cover crop straights and mixtures on the soil surface in 1-mm mesh nylon bags to time N mineralisation within the different residues. N release happened firstly in hairy vetch; a rye-hairy vetch mixture and crimson clover were joint second fastest, and a rye and crimson clover mix and straight rye joint last (Ranells and Wagger 1996). In this study, eight weeks after decomposition it was found that the following kg N/ha had mineralised: 132 from hairy vetch, 108 from rye-hairy vetch, 60 from crimson clover, 48 from rye-crimson clover, and 24 from rye. In addition, the growth stage of cover crops will affect the C:N ratio, for example rye in vegetative form only has a C:N of 26:1, whereas at anthesis this rises to 37:1 before increasing again in mature straw (Clark 2012).

It is possible that the method and timing of cover crop destruction can affect nitrogen release but currently there is little published literature on the methods for destruction, following crop establishment and farming systems. One of the few relevant studies a long term trial (12 years) at the Boigneville Research station compared the effect of three systems of soil cultivation and straw management; Ploughing without cover crops, straw mulched between harvest and winter ploughing and direct drilling without cover crops (Laurent 2007). The speed of nitrogen mineralisation was 0.42, 0.45 and 0.42 kg N ha/standard day for the three systems respectively (Laurent 2007). Therefore direct drilling did not modify the average speed of N mineralisation compared to ploughing. However, direct drilling did reduce nitrate leaching by 8 kg/ha/yr compared to ploughing (Laurent 2006). This work also reported that winter weather conditions affected mineralisation. If winter rainfall was low (less than 50 mm drainage through the soil), the mineralisation of the mustard cover crop did not release enough N to compensate for cover crop uptake. However, if winter rainfall was high, the cover crop prevented nitrate leaching and released sufficient N back to the soil to provide a net benefit. The author concludes that annual fertilisation of following crops may have to be adjusted depending on winter weather conditions (Laurent 2007). Additional information on cover crop destruction and following crop establishment can be found in section 4.1.6.

Main Points

- Mineralisation of most N contained in cover crop residues to plant available forms of N occurs after cover crop incorporation. There may be a residual effect in the second year cash crop after cover cropping.
- Depending on the species and cover crop biomass, destruction method and timing, 10-100 kg N ha^{-1} can be expected to be released in the first year of cash cropping from the preceding cover crop.
- There could be a potential negative effect on soil N in some cases where cover crops such as rye deplete soil N via pre-emptive competition.

Table 4. Typical over autumn/winter N uptake, N release for the following crop and C:N ratio for cover crop species.

Species	Typical autumn / winter N uptake (kg N/ha)	Typical N release for following crop (kg N/ha)	C:N ratio	References
Hairy vetch (*Vicia villosa)*	154	132	11 (8-15)	Reeves (1994) (Clark 2012; Ranells and Wagger 1996)
Rye (*Secale cereale*)	30-61	24	82	Patoja *et al.* (2016), (Clark 2012; Odhiambo and Bomke 2008; Ranells and Wagger 1996)
Crimson clover (*Trifolium incarnatum*)	28	60	11 - 25	Reeves (1994) (Odhiambo and Bomke 2008; Ranells and Wagger 1996)
White senf mustard (*Brassica hirta*)	57 - 116	30-40	Total plant 14; Leaves-9; Stems-19	(Collins et al. 2007; Bugg et al. 2011; Stivers-Young 1998; Silgram et al. 2015)
Oilseed radish (*Raphanus sativus)*	70 -127	10-50	Stem 13; bulb 20	(Dean and Weil 2009; Silgram et al. 2015; Stivers-Young 1998)

3.2. Weed suppression - Allelopathic effects & physical competition

Cover crops can suppress weeds and volunteers either by competition for light, water and nutrients or through the release of allelopathic substances from living or decomposing plant tissue (Creamer et al. 1996; Brennan and Smith 2005). Allelopathy is the stimulatory or inhibitory effect of chemical compounds produced by one plant (including microorganisms) on another plant through the release of chemical compounds into the environment (Rice 1984). This definition was expanded by the International Allelopathy Society in 1966, to refer to any process involving secondary metabolites produced by plants, microorganisms, viruses and fungi that influence the growth and development of agricultural and biological systems (Cheng and Cheng 2015). However, allelopathy is more usually interpreted as the adverse effects of a plant on another plant. Phytotoxic chemicals from plants can enter the environment either through volatilisation, foliar leaching, root exudation, residue decomposition or through leaching from plant litter (Birkett et al. 2001).

Allelochemicals may influence vital physiological processes such as respiration, photosynthesis, cell division and elongation, membrane fluidity, protein biosynthesis and activity of many enzymes, and may also affect tissue water status (Field et al. 2006; Rice 1984). The visible effects of allelochemicals on the growth and development of plants includes inhibited or retarded germination rate, reduced root and shoot extension, necrosis of root tips, discolouration or lack of root hairs, reduced dry weight accumulation and lowered reproductive capacity (Bhadoria 2010; Rice 1984). Allelopathy involves fluctuating mixtures of allelochemicals and their metabolites. These can be regulated by genotype and developmental stage of the producing plant, environment, cultivation and signalling effects, as well as the chemical or microbial turnover of compounds in the rhizosphere (Belz 2007), the level of phytotoxicity in soil and the amount of the allelochemical produced by the plant (Hiradate et al. 2010; Duke 2015). Different crops such as rye (*Secale cerelae* L.), buckwheat (*Fagopyrum esculentum* Moench.), black mustard (*Brassica nigra* L.), and sorghum (*Sorghum bicolor* L.) are reported to be used for weed management (Bhowmik and Inderjit 2002; Weston 1996a). In agricultural systems, cover crops which either exude allelopathic chemicals or produce residues that release allelochemicals that are phytotoxic to weeds can be used to suppress weeds (Batish et al. 2006). Crop residues can also provide weed control by acting as a mulch and through the release of allelochemicals (Weston 1996a). In the case of crop residues, allelochemicals can be either released from residues or produced by microorganisms which feed off the residues (Kruidhof 2008). The use of water extracts of allelopathic plants has also been widely investigated as a spray for weed control. The use of plant extracts as a spray will not be covered in this review. The studies investigated herein are limited to the effects of the crop while growing or as a residue after it has been destroyed.

A large number of biological molecules throughout diverse chemical groups can exhibit allelopathic activity. The majority of allelochemicals are products of secondary metabolism (Albuquerque et al. 2011). However, these metabolites have four main precursors: acetyl coenzyme A, shikimic acid, mevalonic acid and deoxyxylulose phosphate. Based on these precursors, secondary metabolites can be grouped into three main chemical classes: terpenoids, N-containing compounds and phenolic compounds (Albuquerque et al. 2011). Some examples of allelopathic compounds include allyl isothiocyanate in black mustard, fatty acids in buckwheat, isoflavonoids and phenolics in clovers (*Trifolium* species) and sweet clover (*Melilotus* species), phenolic acids and scopoletin in oats, hydroxamic acids in cereals and phenolic acids, dhurrin and sorgoleone in sorghum (Weston 1996a). It has also been suggested that in the field different allelochemicals can act additively or synergistically to inhibit growth (Belz 2007; Kruse et al. 2000; Seigler 1996; Albuquerque et al. 2011). There is quite a body of literature investigating the allelopathy of crops, however the identification of an allelopathic chemical in laboratory conditions does not directly relate to it being produced in the field. Extracts from plants are a means of identifying and isolating chemicals and testing their effects under controlled conditions. It is important that allelopathic effects are confirmed in field conditions. The following section summarises example crops and their reported allelochemicals, how these are affected in the field and any effects on weeds and following crops.

3.2.1. Examples of crops and their allelochemicals

Rye

Rye (*Secale cereal* L.) produces a number of allelochemicals including benzoxazinone, phenolic acids, beta-hydroxybutyric acid, hydroxamic acids (Kruse et al. 2000; Reberg-Horton et al. 2005; Macías et al. 2014). In a review of the allelopthaic potential of rye, 16 allelochemicals were listed (Schulz et al. 2013). The chemical pathway of benzoxazinones was characterised by Macías *et al* (2014). Rye produces 2,4-dihydroxy-(2*H*)$^{-1}$,4-benzoxazin-3(4*H*)one (DIBOA) which is degraded into benzoxazolin-2-one (BOA) and 2-aminophenoxazin-3-one (APO) (Macías et al. 2014). Using rye and wild oat (*Avena fatua* L.) Macías *et al*., (2014) also described the route of the allelochemicals from the donor plant to the target plant (Macías et al. 2014). The levels of benzoxazinoids derived from field-grown rye have been reported to be between 0.5 and 5 kg ha^{-1} (Reberg-Horton et al. 2005; Barnes and Putnam 1987), while the levels from greenhouse grown rye has been reported to greater at between 12 and 20 kg ha^{-1} (Barnes and Putnam 1987; Schulz et al. 2013). DIBOA and BA were found inhibit emergence of barnyardgrass (*Echinochloa crusgalli* L. Beauv.), cress (*Lepidium sativum* L.) and lettuce (*Lactuca sativa* L.) when applied to the soil (Barnes and Putnam 1987). It has been reported that 50% of the initial content of rye residue had disappeared by 105 days after being cut. However, the combined active compound concentrations of DIBOA-glucoside, DIBOA, and BOA disappeared 168 days after clipping (Yenish et al. 1995). The allelopathic potential of rye declines with development (Reberg-Horton et al. 2005), with the period of weed suppression varying from 30-75 days (Weston 1996a).

The production of allelochemicals by rye was found to vary depending on the cultivar and the time of harvest (Reberg-Horton et al. 2005) and the inhibitory effect of rye mulch was found to differ between cultivars (Tabaglio et al. 2008). Tabagilo et al. (2008) showed that of eight glasshouse grown cultivars, all of them produced DIBOA and only four produced BOA. The total benzoxazinoid content ranged from 177 to 545 µg g^{-1} (Tabaglio et al. 2008). The residues of these rye cultivars supressed two of the four weed species tested and suppression ranged from 40% to 74%. Interestingly there was no correlation between the total benzoxazinoid content and the amount of weed suppression (Tabaglio et al. 2008). A series of glasshouse experiments demonstrated that rye shoot residue was affected by fertility, where rye grown under low to moderate amounts of NPK was found to have higher levels of BOA and DIBOA compared to rye grown under higher amounts of NPK (Mwaja et al. 1995). In the field rye mulch has been found to significantly reduce the germination and growth of several problematic agronomic grass and broadleaf weeds (Schulz et al. 2013). The effects of rye and wheat cover crops on a no-till cotton crop were assessed in field experiments in Texas for three years (Li et al. 2013). This study found that the height and yield of cotton after the cover crop was significantly reduced compared to no cover. Allelopathic compounds were detected in the soil including BOA, DIBOA, and DIMBOA). It was concluded that the reduced yield of cotton was partly related to the presence of allelochemicals in the soil (Li et al. 2013).

A study carried out in Sweden investigated the allelopathic effects of wheat-rye translocation lines, a triticale cultivar (Dinaro; wheat & rye cross) and wheat on black-grass (*Alopecurus myosuroides* Huds.) (Bertholdsson 2012). Potential allelopathic activity was assessed by a bioassay in the lab which assessed a reduction in root growth. This was followed by two years of testing a subset of material in the field. Nine winter wheat and one triticale cultivar were sown in field trials. A heavy population of black grass was present either naturally or through hand spreading. Crop and black grass biomass was assessed at crop heading/booting. Bertholdson found that cultivars with a high allelopathic activity tended to have less black grass biomass at heading of wheat than those with low activity. It is interesting to note that in both years of the field study the triticale cultivar had the highest allelopathic activity and inhibition of black-grass, closely followed by wheat cultivar Nimbus. Cultivars with high allelopathic activity gave only half the black-grass biomass of cultivars with low allelopathic activity, and the author suggests that choice of cultivars with high allelopathic activity is likely to be important in integrated weed management of black-grass (Bertholdsson 2012).

Barley

Phytotoxic phenolic compounds have been identified in cold water extracts of barley (*Hordeum vulgare* L.) straw as well as in methanol extracts from living barley roots (Albuquerque et al. 2011). Two alkaloids, gramine and hordenine, were the first allelochemicals identified to explain the allelopathic effects of barley (Overland 1966; Liu and Lovett 1993b). The allelopathic action of the alkaloids gramine and hordenin have been confirmed (Albuquerque et al. 2011). However, forty four compounds belonging to different chemical classes have been identified as potential allelochemicals in barley (Kremer and Ben-Hammouda 2009). Graminine has been located in barley leaves and released to the environment by rain (Yoshida et al. 1993). Hordenine has been found in barley roots cultured in a hydroponic system from the first day of germination up to 60 days later (Liu and Lovett 1993a). Interestingly, selection for agronomic traits in barley appears to have unintentionally favoured hordenine biosynthesis, the ability to synthesize gramine seems to be reduced or even lost in modern cultivars (Lovett and Hoult 1995). In field studies under no-tillage, spring barley residues reduced weed densities by up to 90% compared with soils devoid of surface residues. (Putnam et al. 1983). In a field experiment in Greece, a mulch of barley (and other winter cereals) reduced barnyardgrass and bristly foxtail (*Setaria verticillata*) seed germination and growth. The barley and other winter cereals were incorporated into the top 8-10 cm of soil in the spring, and 15 days later weed seed were broadcast and incorporated into the top 5 cm of soil. Four weeks after planting corn, barnyardgrass and bristly foxtail emergence was reduced by 27 – 80% and 0 – 67% respectively compared to un mulched plots (Dhima et al. 2006). At harvest, corn yield increased by 45% in the plots mulched with barley cultivar Athinaida, and receiving no herbicide, compared to respective mulch free treatments (Dhima et al. 2006).

Sorghum

Sorghum (*Sorghum bicolor* L.), is another crop reported to have allelopathic effects. The allelochemicals found in *S. bicolor* include dhurrin (Gorz et al. 1977) sorgoleone (Netzly et al. 1988), strigol and sorgolactane (Hauck et al. 1992). The most studied metabolites, exuded by the roots of sorghum are a group of hydrophobic benzoquinones called sorgoleone (Czarnota et al. 2001; Czarnota et al. 2003a). The root hairs produce and release high quantities of an oil-like substance containing 80-95% sorgoleone (Dayan et al. 2007). Sorgoleone has a half-life of more than 77 days in some soils (Gimsing et al. 2009) and has been reported to inhibit the growth of many weeds (Alsaadawi and Dayan 2009; Einhellig and Souza 1992; Netzly and Butler 1986). The allelopathic effect of sorgoleone has been reported to inhibit electron transport in photosystem II (Czarnota et al. 2001) and to disrupt the biosynthesis of carotenoids (Weir et al. 2004). It can also interfere with root H^+-ATPase and water uptake (Hejl and Koster 2004). In experiments to test the effect of sorgoleone, it was demonstrated that it inhibits photosynthesis in newly germinated seedlings but has no effect on older plants (Dayan et al. 2009).

The incorporation of sorghum roots in experiments in Pakistan was found to supress weed biomass by 25-50% and increased wheat yields by 7-8% (Cheema 1988). While the incorporation of sorghum stalks at 2-6 t ha^{-1} at sowing was found to control up to 40-50% of weeds (Cheema and Khaliq 2000). In field experiments in Iraq over two years, the incorporation of sorghum residue was reported to reduce weed density and biomass (Alsaadawi et al. 2013). Additionally, greater weed inhibition was observed with higher amounts of residue. These authors also combined the sorghum residue with applications of the herbicide Trifluralin, and found that at 50% of the label full dose combined with the sorghum residue gave similar or greater weed suppression than the herbicide alone (Alsaadawi et al. 2013). This was taken as evidence to suggest that a low dose of herbicide combined with allelopathic conditions could help to minimise herbicide use. Sorghum phytotoxins were found to be released in high quantities in the field during the early stages of residue decomposition (first 40 days) (Alsaadawi et al. 2013). Varietal differences in the allelopathic activity of sorghum have been detected (Czarnota et al. 2003b) and sorgoleone exudation can be affected by plant age and environmental factors (Hess et al. 1992). As well as varietal, growth stage and environmental effects the production of sorgoleone in sorghum roots has also been found to be stimulated by a crude extract of velvetleaf (*Abutilon theophrasti* Medic) (Dayan 2006).

Hairy vetch

Hairy vetch (*Vicia villosa* Roth.) has been reported as good weed suppressive mulch, although the literature is not always consistent. For example, in one field study incorporated hairy vetch suppressed the biomass of redroot pigweed (*Amaranthus retroflexus* L.) and lamb's quarters more than brown mustard (*Brassica juncea* L.), rye or bare soil (Ercoli et al. 2005). In a growth room study using aqueous extracts the germination of lambs quarters was suppressed by about 20%, but the germination of redroot pigweed and common knotgrass (*Polygonum aviculare* L.) was not (Ercoli et al. 2007). In a different study using a filter paper bioassay, there was no germination of kochia and lamb's quarters in the presence of aqueous extracts of hairy vetch (Geddes et al. 2015) with more moderate effects found in soil. Teasdale *et al*., (2007) found in a glasshouse assay using field grown hairy vetch, that vetch mulch harvested just before or just after desiccation suppressed the emergence of several annual weed species (velvetleaf (*A theophrasti* Medic.), green foxtail (*Setaria virdis* L.) and smooth pigweed (*Amaranthus hybridus* L.)) more than vetch residue which had been in the field for one month. (Teasdale et al. 2007).

Brassicaceae

The Brassicaceae family, including wild radish (*Raphanus raphanistrum* L.), white mustard (*Sinavis alba* L.) and turnip (*Brassica campestris* L.) have also been reported to have allelopathic potential (Haramoto and Gallandt 2004). The effects on microorganisms/pests is well documented and is also considered in section 3.3 on biofumigation. Glucosinolates are released into the environment through either volatilisation or decomposition. After release, glucosinolate is decomposed into several biologically active compounds, such as isothiocyanate (Morra and Kirkegaard 2002). Isothiocynthates can suppress the growth and development of plants (Petersen et al. 2001). For example the isothiocyanates from Turnip-rape (*Brassica rapa*) mulch were found to significantly suppress black-grass germination (Petersen et al. 2001). In another field study in Turkey, oilseed rape (*B. Napus*), field mustard (*B. rapa*) and oriental mustard (*B.juncea*) were grown as cover crops in a hazelnut orchard. The cover crops were incorporated in to the soil at the flowering stage. The cover crop treatments reduced weed density, dry weight and the number of weed species when compared with the fallow treatment (Mennan and Ngouajio 2012). The cover crops residues had inhibited germination of the annual weed species compared with the no cover crop control, however the residues had not suppressed many of the perennial weed species and those which were difficult to control using herbicides.

Sunflowers

The use of sunflowers (*Helianthus annuus* L.) as a green manure was found to reduce the population of littleseed canarygrass (*Phalaris minor* Retz.), by 100% under laboratory conditions and 42% and 15% under field conditions (Om et al. 2002). In an experiment in Iraq evaluating eight sunflower cultivars, the residues supressed weed density by 24-75% and total weed biomass by 12-67% compared to the untreated control (Alsaadawi et al. 2012). These cultivars were also grown with weeds, and reduced weed density (24-75%) and total weed biomass (12-67%). The cultivars with the higher concentrations of phenolic acids had the greatest effect on weed suppression (Alsaadawi et al. 2012). In a five year study with a sunflower and oat rotation, the weed density was significantly less in sunflower plots compared to control plots (Leather 1983a, b, 1987).

There is limited evidence in the literature of field based allelopathic effects of cover crops and very limited information based in the UK. The effects of allelochemicals from cover crops and cover crop residues needs to be tested in the field, as laboratory and glass house assays do not always indicate effectiveness in the field. Some of the weed species cited in the literature above are included to illustrate the point, but are not relevant to UK agriculture. One other important issue relating to allelopathy is the ability to determine if weed suppression is the effect of allopathy or competition, which can be difficult and the effects can be variable.

3.2.2. Differentiation of allelopathy and plant competition

Apart from allelopathy, the other main weed suppression ability of cover crops is physical competition relating to early light interception (Kruidhof 2008) and resource competition (Lawley et al. 2012). The impact of early light interception on weed suppression is dependent on the relative height increase of the target weed species compared to the cover crop species, with smaller weed species, such as annual meadow grass (*Poa annua* L.) and common chick weed (*Stellaria media* (L.) Vill.), affected throughout the period of the cover crop, but taller species, such as fat hen (*Chenopodium album* L.) affected only in the early stages of establishment before out-growing the height of the cover crop (Kruidhof 2008). Variation in competitive ability exists between species and between cultivars within a species. Increased competitive ability has been attributed to early emergence, seedling vigour, rapid growth (biomass, expansions and height) and rate of canopy closure. For example, by producing a dense canopy rye cover crops compete effectively with weeds for light, moisture, and nutrients, resulting in a suppression of their growth (Weston 1996b). Brennan and Smith (2005) found in a tilled vegetable system on the central coast of California that a legume and oats mix, allowed burning nettle to produce large amounts of seed due to poor early season growth, and that this may increase weed management costs in subsequent crops. This study evaluated three cover crops and of these mustard was reported to be the best for weed control given its early season growth and weed suppressive abilities (Brennan and Smith 2005).

The differentiation between allelopathy and plant competition or suppression is not always addressed in the literature and it can be challenging to isolate these effects from each other (Rice 1984; Blum 2007; Fujii 2001). Duke (2015) highlights another potential complication; that the plant making the allelochemical may only make sufficient amounts for an allelopathic effect when in the presence of a targeted plant species (Duke 2015). For example, as mentioned above, the production of sorgoleone by sorghum roots was stimulated by a crude extract of velvetleaf (Dayan 2006). Likewise, an allelopathic rice variety was reported to exude significantly more phytotoxins from its roots in the presence of the rice weed barnyardgrass (*Echinocloa crus-galli* (L. Beauv.) than when growing in monoculture (Kong et al. 2004).

An interesting set of field and laboratory experiments have attempted to separate the physical effects from the chemical effects of weed suppression. For example, when weed suppression of rye mulches were compared to inert mulches, such as bark, no allelopathic affect was found, with weed suppression caused by physical impedance and light deprivation (Teasdale et al. 2007), 2000). Creamer et al. (1996) extracted allelochemicals from rye, crimson clover (*Tincarnatum* L.), hairy vetch (*V villosa* Roth.), barley (*H vulgare* L.) and used the re-dried biomass as an inert control. In the field, the dried (leached) shoot residues of each species and a mixture of the four species suppressed the emergence of eastern black nightshade (*Solanum ptycanthum* Dun.), showing a physical component to weed suppression by cover crops, probably due to the exclusion of light (Creamer et al. 1996). These authors also found that crimson clover inhibited the emergence of eastern black nightshade beyond what could be attributed to physical suppression alone. Lawley *et al*., (2012) reported on four different experimental techniques (including field trials) to identify the mechanism of weed suppression by forage radish (*Raphanus sativus* L.). The conclusion of the four experiments and previous field work (Lawley et al. 2011) was that competition of weeds in the autumn by the radish, due to rapid canopy development, is the dominant mechanism for early spring weed suppression following the cover crop (Lawley et al. 2012). These authors found no allelopathic activity from the fodder radish. A series of field experiments in Germany between 2013 and 2015, found that mustard (*Sinapis alba* L.), fodder radish and spring vetch (*V. sativia* L.) suppressed weeds by 60% and cover crop mixtures controlled weeds by 66% during the cover crop period (Kunz et al. 2016). Corresponding laboratory tests, using aqueous extracts of the cover crops extended germination time by 54% compared to a water control (Kunz et al. 2016). These authors also found a positive correlation between weed density in the field and weed root length in the laboratory tests, suggesting that allelochemicals played a role in the weed suppression in the field (Kunz et al. 2016).

Many studies regarding cover crop weed suppression are conducted worldwide, but European literature is scarce, especially in relation to reduced tillage systems (Melander 2013). An example of this scarcity is the lack of data on the effect of cover crops in suppression of black-grass (*Alopecurus myosuroides* Huds.), the UK's worst herbicide resistant weed (Moss 2007). The available data on the ability of cover crops (mixes or straights) to suppress black grass populations is limited and can be anecdotal. A recent AHDB funded project (Moss et al. 2016) found that sowing a spring wheat crop gave a 92% reduction in blackgrass plants emerging compared to September sown wheat. This illustrates the value of spring cropping for blackgrass control which will provide more opportunities for growing cover crops. The added value fallows project (funded by AHDB) aims to incorporate cover crops in fallows which can enhance weed suppression as well as delivering other added benefits. Cover crops in the project include a biofumigant brassica, conventional brassica, LegLINK mix and white clover.

3.2.3. Confirmation of allelopathy and weed competition in the field

It is important that allelopathic effects are confirmed in field conditions and how they might be affected by soil texture, organic matter, temperature, light and microbial breakdown (Bais et al. 2006; Blum et al. 1999). Belz (2004) comments that the allelopathic potential of a certain cultivar may differ considerably in different environments and a clear understanding of the genotype by environment interactions is needed if it is to be a reliable option for weed management (Belz 2004). Macías *et al*., (2014) suggest that the exudation, uptake dynamics and degradation products should be considered when characterising allelopathic phenomena (Macías et al. 2014). Duke (2015) states that proof of allelopathy is difficult to obtain. In the field, biotic and abiotic factors can enhance or reduce allelopathy (Duke 2015). Effectively, crop allelopathy is a dynamic process across developmental stages of both the crop and the weed (Belz 2007) and the net outcome will vary with scenario.

One of the main knowledge gaps relating to cover crop weed suppression abilities is the impact cover crops have on UK relevant weed populations in the following cash crop and in the rotation. Results from studies are contradictory, with some studies showing no effect on weed suppression in the following crop, (Lawley et al. 2011; Swanton et al. 1999; Haramoto and Gallandt 2004); others showing early season weed suppression but not full-season weed control (Teasdale 1996); whilst others show weed suppression well into the cash crop season (56 days after cover crop incorporation) (Isik 2009). The effect of cover crops on seed bank density and therefore weed burden in cash crops can vary dramatically depending on the cover crop used and the weed species. Over an experimental period of 7 years in a maize-wheat crop rotation rye cover crops reduced the weed seed bank density by 25%, whilst a crimson clover cover crop had no significant effect (Moonen and Bárberi 2004). Furthermore, the effect of cover crop species on weed seed bank density varied significantly depending on target weed species and tillage system (Moonen and Bárberi 2004), showing that cover crop species selection needs to vary depending on target weed species and farming system, and that the cover crop system (species and cultivations) must be tested in a practical context (Melander 2005).

Main Points

- A number of cover crops have been reported to have in-field allelopathic effects including rye, oats, barley, wheat, triticale, brassicas (oilseed rape, mustard species, radishes), buckwheat, clovers, sorghum, hairy vetch, sunflower, fescues
- The release of allelochemicals can be affected by plant age and vigour and environmental factors. They may also be affected by the presence of other plants
- The impact of allelochemicals in the field can be affected by soil texture, organic matter, temperature, light and microbial breakdown
- It is not easy to separate the effects of physical competition from that of allelopathic effects
- Increased competitive ability is linked to early emergence, seedling vigour, rapid growth and canopy closure
- It is important that allopathic and competitive effects are confirmed in field conditions and the effects on UK relevant weed populations which are evaluated in the cash crop
- The effect of cover crops on seed bank density and therefore weed burden in cash crops can vary dramatically depending on the cover crop used and the weed species

3.3. Biofumigation effects

A variety of brassica species are used as biofumigant crops to control soil borne pests, especially plant parasitic nematodes. Biofumigation can also control weeds and diseases, however, the main use is for the control of pests. The effect of biofumigation occurs when cover crop material is chopped up and incorporated into the soil, releasing glucosinolates and products of their degradation, such as isothiocyanates (ITCs) and volatile sulphur compounds that are toxic to soil pests. Biofumigant cover crops have been demonstrated at the field scale as a useful tool in managing beet cyst nematode (*Heterodera schachtii,* Hauer *et al.* 2016) and rhizoctonia root rot in sugar beet (Motisi et al. 2013), and potato cyst nematode (*Globodera pallida, G rostochiensis*) in potatoes (Ngala et al. 2015). Different brassica species produce different levels and types of biofumigant compounds, and each has a different effect on different nematode species (Lord et al. 2011). Lord *et al.* (2011) identified three *Brassica juncea* lines that were 95% effective at killing *G. pallida* eggs in a pot trial, with *B.juncea* residues incorporated into both open and polyethylene covered soil pots containing *G.pallida* cysts and eggs, Ngala *et al.* (2015) investigated biofumigation with three brassicas *:B. juncea*, *Raphanus sativus* and *Eruca sativa* at the field scale in Shropshire, UK. Summer cover crop cultivation and autumn-incorporation was compared with over winter cover crop cultivation and spring incorporation. In the autumn incorporation trial, the *G. pallida* population was significantly reduced in the *B. juncea* cover crop plots. In the spring incorporated trials there was no significant effect of cover crops on nematode population (Ngala *et al.* 2015). As well as a biofumigant effect some brassica species promote nematode hatching but do not allow completion of their life cycle and therefore deplete nematode levels in soil (Fourie et al. 2016). This was observed in the field in the UK by Ngala *et al.* (2015) in plots with autumn incorporated *B. juncea*, which reduced the multiplication rate of *G. pallida* nematodes. Clarkson (2014) investigated the effect of brown mustard, forage rape, a rye and clover mix, wheat and white mustard cover crops in the field on carrot cavity spot (*Pythium violae*), Sclerotina (*Sclerotina sclerotiorum*) and free living nematodes. It was reported that "although ITCs from mustard biofumigants can inhibit both *P. violae* and *S. sclerotiorum*, it is clear that demonstrating this effect in the field is challenging" (Clarkson 2014). It is noted that the efficacy of biofumigation can be affected by agronomic factors and environmental factors which result in low growth and low glucosinolate levels, poor conversion of glucosinolates to ITCs, inefficient crushing/incorporation of plant material and inadequate soil moisture levels (Clarkson 2014).

Main Points

- Brassica cover crops (e.g. *B juncea,* mustard greens; *R sativus,* oilseed radish) release glucosinolates and volatile sulphur compounds that are toxic to many soil borne pests and can be used to biofumigate soils and help combat pests such as potato cyst, beet cyst or free living nematodes

3.4. Erosion and runoff

The risk of soil erosion is high if land is bare and there is significant rainfall. Soils on sloping land are especially at risk from erosion. The impacts of soil erosion can be both short term such as loss or damage to crops, or long term such as loss or redistribution of fertile soil in fields (Posthumus et al. 2015). Surface runoff occurs where excess rainfall flows across the soil surface. This flow of water can cause soil erosion, as sediment is carried with the flowing water, and leaching of pesticides or loss of nutrients such as phosphorous (P) or heavy metals (Mirás Avalos et al. 2009; Schindler et al. 2009). For example, annual edge of field P losses due to soil erosion of 2300 tonnes were recorded from at risk fields in England and Wales over six years (Chambers 1998). In arable areas receiving both inorganic fertiliser and animal manures, a soil P surplus is common and there is a risk of leaching excess P via runoff or sediment erosion (Withers *et al.* 2001). Over winter cover crops are thought to combat soil erosion and runoff as they provide canopy cover to prevent high energy raindrops hitting the soil directly, while their root systems stabilise the soil and improve rainwater infiltration by slowing down the flow of water and creating more soil channels (reviewed in Davidova *et al*. 2015). Wind erosion is reduced as the cover crop increases surface roughness reducing the wind speed close to the soil, and cover crop root systems also have a binding effect on the soil. Newell-Price (2011) cite a 20-80% reduction in P and sediment loss by growing an over winter cover crop. Cover crops were found to reduce run off and soil erosion by rain substantially at ground covers of greater than 75% in (Enwezor 1976). Kainz (1989) showed that a percentage soil cover of 30% can reduce run-off by up to 50% and erosion by up to 80%. A cover crop of ryegrass over sown into maize crops in June can be effective at reducing over winter sediment losses by 70%, reducing surface runoff by 40-60% and nitrate leaching losses compared to a standard maize stubble (Smith 2016).

There are data available on the effect of cover crops on erosion and runoff generated from computer simulations, and field experiments with either simulated or natural rain events on a variety of soils. Basche *et al.* (2016) used a simulated computer model to estimate the effect of an over winter rye cover crop compared to an over winter fallow soybean and maize rotation in the Midwestern USA. They found a 11-29% reduction in soil erosion in the presence of a cover crop scenario compared to no cover crop (Basche et al. 2016). For the UK, the FARMSCOPER model (Gooday et al. 2013; Gooday and Anthony 2010) will predict the impact of sowing a cover crop in the autumn on nitrate, P and sediment losses, using data from the Defra Mitigation Method User Guide (Newell-Price 2011). Examples are given in Gooday et al. (2013) that cover crops can reduce nitrate, P and sediment losses by 4%, 1.9% and 2.2% respectively on a cereal farm and by 4.4%, 3.5% and 4.2% respectively on a dairy farm. Davidova *et al.* (2015) used irrigation to simulate rainfall in field experiments on loamy sands in the Czech Republic to estimate the effect of canopy cover of oats on soil erosion and runoff. They determined a significant decrease in soil erosion with increasing oat canopy cover, but there was no significant effect of canopy cover on surface runoff. Simulated rainfall events in this study were during July and August on autumn sown crops, with canopy cover of 80% and above. There is limited data from this study applicable to the lower canopy cover that would be present in over winter cover crops of oats. Zhu *et al.* (1989) showed on a poorly drained clay soil with a 3% slope in the Midwest USA, over winter cover crops of chickweed (*Stellaria media*), downy brome (*Bromus tectorum*) and Canada bluegrass (*Poa compressa*) as straight, unmixed stands reduced both soil erosion and runoff between December and January. Cover crops were broadcast in mid-September and following soybean crops were direct-drilled into cover crop stands in May. Compared to overwinter stubble, the downy brome cover crop reduced soil erosion by 95% and runoff by 53% (Zhu et al. 1989). In south Sweden, Ulen *et al.* (1997) measured loss of P in runoff from clay loam soils on a slope with either over winter stubble or cover crops of wheat or ryegrass (*Lollium perenne*). P losses due to runoff were not significantly decreased by overwinter cover crops in this study. In the UK, a reduction in run-off with the use of cover crops has been demonstrated by Stobart and Morris (2014). Cover cropping with white clover as a clover bi-crop on a sandy loam site was shown to improve infiltration rates to 2.19 mm per minute compared to non-cover cropped areas which had an infiltration rate of 0.78 mm per minute (Stobart and Morris 2014).

Main Points

- Overwinter cover crops have the potential to decrease soil erosion and run off if sufficient canopy cover (soil cover of 30% can reduce run-off by 50% and erosion by up to 80%) and root establishment is achieved, dependant on the species used.
- The FARMSCOPER model can be used to predict the impact of sowing an autumn sown cover crop on nitrate, P and sediment losses.

3.5. Effects on soil health & fertility

Soil health, fertility and structure are key factors that influence soil function. Central to this is the widely recognised role of soil organic matter (SOM) in the maintenance of soil fertility and function through the provision of nutrients and energy which drive the many soil biological processes that underpin soil structural development, nutrient and water availability (Kibblewhite et al. 2008). Organic matter provides a food source and habitat for the soil biological community which, during the process of decomposition, release organic compounds or ‘glues’ that, together with fungal hyphae and the actions of soil macrofauna (e.g. earthworms), bind soil particles together to form stable aggregates and pores, thereby improving soil structure and porosity (Tisdall and Oades 1982; Fawcett and Caruana 2001; Lipiec et al. 2005; Bronick and Lal 2005). Organic matter inputs to soils are a source of valuable plant nutrients and also provide the energy source which drives the many biologically mediated processes involved in nutrient transformations as well as contributing to the soils cation exchange capacity (Powlson et al. 2015). Consequently maintaining and enhancing SOM is fundamental to improving soil fertility and function, with SOM recognised as a key indicator of soil 'quality' (Anon 2009). The impact of cover cropping on soil organic matter are highlighted in the following section followed by a review of the effects of cover crops on other soil physical and biological properties.

3.5.1. Soil organic matter and carbon

Soil organic matter (SOM) has been defined as any material produced originally by living organisms (plant and animal) that is returned to the soil and goes through the decomposition process (Bot and Benites 2005). SOM is an important carbon store, so soil organic carbon (SOC) is a property which is often used interchangeably in discussions of the effect of management practices on soil organic matter. However, SOM is different to SOC in that it includes all the elements (hydrogen, oxygen and nitrogen etc.) that are the components of organic compounds, not just carbon (Pluske et al. 2016) Organic matter is commonly analysed in experiments and reported as either SOM or SOC, and whilst they are not directly measuring the same components a conversion factor of 1.72 is commonly used to convert SOC to SOM (Pluske et al. 2016) This conversion factor assumes SOM contains 58% organic carbon; however, this can vary with type of organic material, soil type and soil depth.

The decomposition of organic materials in soils tends to occur rapidly in the first few months following incorporation, followed by a much slower phase. This has led to the conclusion that organic matter comprises of at least two different fractions: a labile fraction with a fast turnover time and a more resistant fraction with a slow turnover time (Milne and Smith 2015). Freshly added or partially decomposed plant residues and their non-humic decomposition products comprise the labile (or active) organic matter pool (Gregorich et al. 1997; Loveland et al. 2001), with the soil microbial biomass either included within this pool, or considered as a separate pool for modelling purposes (Milne and Smith 2015).

Measurement of these biologically active fractions of SOM that change rapidly over time, could better reflect changes in soil quality and nutrient dynamics due to changes induced by crop management practices, such as cover cropping (Sainju et al. 2007), particularly as the effect of such practices on the total SOM pool is often difficult to detect due to the large background concentration of SOM within the soil (Bhogal et al., 2009). The active SOM pool within a soil can be quantified by measuring a number of physical fractions: free light fraction (FLF), intra-aggregate light fraction (IALF) and heavy fraction (HF). The FLF is composed of organic matter from microbial and micro fauna, seeds and root fragments (Golchin et al. 1997). The IALF is associated with aggregates and includes organic compounds such as plant residues, faecal pellets, pollen grains, root hairs and fungal structures (Figueiredo et al. 2010; Nascente et al. 2013). The HF is composed of organic material which is not visually identifiable, tightly bound to soil minerals and the primary organo-mineral complexes (Christensen 2000; Sohi et al. 2001; Nascente et al. 2013). The light fraction of SOM has been demonstrated to be particularly involved in soil structural development (e.g. Tisdal & Oades, 2982; Loveland et al., 2001) and therefore it has been hypothesised that regular addition of fresh organic residues will improve soil structure (Shepherd et al. 2002). Crop root systems and non-harvested residues are also an important input (Shepherd et al. 2002).

The decomposition of organic materials in soils is highly dependent on soil temperature and moisture (Whitmore 2007), soil type (Hassinnk 1994) and the composition of the applied materials (particularly the C:N ratio (Chadwick et al. 2000)). In general, organic materials with a C:N ratio greater than 30 (1.2 – 3% N) will cause immobilisation of soil/fertiliser and minerals, while organic materials with a ratio of less than 20 (1.8 – 20 % N) will result in net mineralisation (Jenkinson 1984). Therefore, as a rough guide, a C:N ratio of 25:1 is often quoted as the ratio at which a residue will either mineralise N or immobilise it. Cover crops with a lower C:N ratio, such as legumes, therefore break down more quickly once incorporated and have less effect on long-term organic matter (Rayns and Rosenfeld 2006).

Any crop which is grown, and its residues then incorporated into the soil will add organic material to the soil with the potential to increase SOM levels. However, it is difficult to detect changes in SOM and SOC from cover crop treatments or the addition of cover crops to a cropping system and a number of studies have reported on no changes in either SOC or SOM. As outlined above this may also be because it is difficult to measure small changes in SOM in field soils which have relatively high background levels and large variations in SOM with depth (Kaspar and Singer 2011; Kaspar et al. 2006; Bhogal et al. 2009). It may also be a consequence of the length of time the cover crop treatments have been in place (Kaspar and Singer 2011; Moore et al. 2014) such that the cover crop may not produce sufficient amounts of biomass, or the biomass produced may be small compared to the amount produced by the cropping system (Kaspar and Singer 2011). Consequently, studies evaluating the effect of cover crops on SOM/SOC have given rise to variable and conflicting results.

For example, a rye cover crop in a no-till continuous corn or corn/soybean rotation did not increase soil C (Eckert 1991). After 13 years of a crown vetch (*Coronilla varia*L.) living mulch treatments, there were similar SOC levels with the control (Duiker and Hartwig 2004). The authors suggested that the suppression of the crown vetch with a herbicide programme in order to prevent competition with the corn crop reduced the potential benefits on SOC. Additionally, neither a red clover or triticale winter cover crop increased soil carbon in a vegetable production system (Mendes et al. 1999). An eight year study of three different tillage systems with and without cover crops found that there was no statistical difference between the SOC levels and that no soil carbon sequestration (net increase) occurred over time for any of the tillage treatments with cover crops (Olson et al. 2010). In contrast a 12 year cover crop experiment in Southern Illinois found that the SOC stocks in the root zone (0-75 cm) significantly increased with cover crop treatments under two of three different tillage regimes compared to the pre-experiment baseline by between 5.9 and 10.2 Mg C/ha/layer (Olson et al. 2014). In a different study, four years after a conservation tillage cotton-winter rye cropping system in Alabama, USA, the soil carbon in the upper 5 cm was 25% and 42% greater than under cotton-winter fallow and bare fallow respectively (Parker et al. 2002). Additionally, a three year study in Georgia USA, found that the input of cover crop biomass (sunn hemp and crimson clover) increased soil C (0.3 to 4.7 mg g^{-1}) and N (0.1 to 0.5 mg g^{-1}) in the top 2.5 cm, although these changes were not statistically significant, and contributed to improvements in soil structure, shown by decreases in bulk density (BD) and increases in saturated hydraulic conductivities and volumetric contents (Hubbard et al. 2013). Hairy vetch (*V villosa*) as a cover crop was found to significantly increase soil organic matter by 0.31 % and aggregate stability by 3 index points significantly compared to the control (the aggregate stability index ranges from 1 to 32, and a higher value corresponds to a higher aggregate stability (Niewczas and Witkowska-Walczak 2003) in the top 10cm of soil compared to a cash crop residue control in a long term field study (Sapkota et al. 2012). Sainju et al. (2002) observed a 25% decrease in SOC following six years of conventional tillage without cover crops, whereas with a hairy vetch cover crop (returning *c.* 0.7 t C ha^{-1} yr^{-1}) SOC levels only declined by 1 % and with a rye cover crop (returning *c.* 3.7 t C ha^{-1} yr^{-1}) SOC levels increased by 3-4 %.

Other studies have measured different fractions of the SOM pool, as a potentially more sensitive indicator of the impact of cover cropping on SOM (i.e. where differences in the total SOM pool cannot be detected). For example, a rye cover crop was shown to increase microbial biomass and potential carbon mineralisation compared to hairy vetch, crimson clover and no cover due to greater biomass yield and C content (Sainju et al. 2003). However even using SOM fractions (e.g. biomass C, C mineralisation rates or physical fractionation, as outlined above), the conclusions have been variable.

For example, Mendes et al. (1999) reported that in September 1995 soil microbial biomass carbon (MBC) was greater where cover crops were present than in bare fallow, but in June & September 1996 there was little difference between these treatments. In contrast potential carbon mineralisation was greater with cover crops than in fallow in September 1996 (Mendes et al. 1999). In a later study a mix of hairy vetch and rye was found to increase crop biomass C and SOC compared to each species on its own or no cover (Sainju et al. 2006; Sainju et al. 2005). A rye and a legume mix and straight rye in a tillage cotton rotation gave greater C inputs over two years than a mix without rye and straight crimson clover (Sainju et al. 2007). Soils under millet cover crop, in a two year cover-rice rotation, were found to have the highest accumulation of carbon at 19.5 g kg^{-1} compared to 17.5 g kg^{-1} in the fallow and N of 1.09 g kg^{-1} compared to 0.90 g kg^{-1} in the fallow (Nascente et al. 2013). This study concluded that the use of cover crops such as millet increased C and N concentrations in the light fractions of the SOM, and that SOM fractionation is a good indicator of differences in soil management in the organic matter dynamics in a short period of time (Nascente et al. 2013). A long term cover crop experiment (established in 1990) in Massachusetts (USA) reported that after 16 years the organic carbon and light fraction (LF) was greatest in soil from the vetch/rye and rye management systems, compared to the no cover crop system (Ding et al. 2006). This is because the no cover crop system had lower plant residue inputs than the cover crops systems (Ding et al. 2006). Ding et al (2006) examined the chemical and structural SOM characteristics (humic acids and fulvic acids) and found that the different cover crops had a significant effect on these.

A winter wheat cover crop in a cotton rotation for 21 years increased SOC under conventional tillage between 3 and 12 cm soil depth and increased microbial biomass to 6 cm depth, as a result of increased crop residue return. However, cover cropping was not found to significantly affect soil microbial biomass C under no tillage at any depth (Motta et al. 2007). The effect of ten years of incorporation of the legume horsegram (*Macrotyloma uniflorum*) in a sorghum and sunflower rotation in India was a 24% increase in mean organic carbon content compared to fallow (Venkateswarlu et al. 2007). Interestingly, cover crop incorporation together with fertiliser application maintained a stable sorghum yield over the ten years, whereas yield declined with fertiliser application alone (Venkateswarlu et al. 2007). A long term field experiment (10 years) in Iowa, demonstrated that the average SOM was 15% greater with a rye cover crop after corn silage and soybean than no cover crop at 0 – 5 cm depth (Moore et al. 2014). At 5 to 10 cm depth, the SOM was 5% higher with the rye cover crop after silage and soybean than the no cover crop and rye after soybean treatments (Moore et al. 2014). It is suggested that because the cover crop residues were not incorporated into the 5 – 10 cm soil layer that the SOM in this layer would change more slowly and would be more dependent on root residues (Gale and Cambardella 2000; Moore et al. 2014).

In a long term experiment in Italy, 15 years of the cultivation of cover crops has led to a significant increase in SOC concentration in the top 30 cm of soil. On average the leguminous cover crops increased SOC by 10% in the top 10 cm of soil and by 8% in the 10 – 30 cm soil layer (Mazzoncini et al. 2011). The non-legume cover crops (brown mustard or rye) also increased SOC, but to a lesser extent (6% and 3% in the 0-10cm and 10-30cm soil layers respectively) and were not significantly different from the control (Mazzoncini et al. 2011). In the same study the non-legume cover crops increased SOC content by 0.08 t ha^{-1} year^{-1}, the 'low nitrogen supply legume' cover crop (crimson and squarrosum clover) increased the SOC by 0.32 t ha^{-1} year^{-1}, and the 'high nitrogen supply' cover crop (subterranean clover and hairy vetch) increased the SOC by 0.34 t ha^{-1} year^{-1} (Mazzoncini et al. 2011).

A meta-analysis of 30 studies (37 sites), including sampling depths which ranged from 2.5cm to 120cm   found that the use of cover crops as a green manure led to a significant increase in SOC stocks (Poeplau and Don 2015). The time since cover crop introduction also influences the SOC stock exchange, with a mean accumulation rate of 0.32 ± 0.08 t C ha^{-1} yr^{-1} to an average maximum increase of 16.7 t ha^{-1} (Poeplau and Don 2015). The authors suggest that these increases are similar to other organic input C sequestration management options for agricultural soils. However, it should be noted that livestock manure applications can increase SOC by 0.5 – 2.5 t/ha/yr (Dawson and Smith 2006). It is noted that more work is needed to understand the species-species effects on SOC stocks and N_2O emissions (Poeplau and Don 2015).

Overall, the evidence base suggests that the effect of cover crops on the total SOM or SOC content of a soil is highly variable and difficult to detect, particularly in short-term studies and with low-yielding cover crops. A number of studies have reported no change in SOM or SOC, whereas other studies have reported increases in SOM ranging from 0.3% up to 42% relative to treatments without a cover crop. Importantly, no study reported a decline in SOM. The extent of the effect appeared to depend on the length of the experiment (i.e. number of years of cover cropping) and cover crop species and mix, although it is not possible to identify particular species or mixes that were most beneficial. Where an effect on the total SOM pool cannot be detected, there is some evidence to suggest that measurement of other organic matter fractions, including the microbial biomass may provide a more sensitive indicator.

3.5.2. Soil physical properties & structure

Soil structure refers to the size, shape and arrangement of solids and air spaces, the continuity of pores, the ability to retain and transmit fluids and the ability to support root growth (Morris et al. 2014). The physical and chemical properties of soils are therefore crucial to crop growth (as is the soil biological component, which is discussed in the following section). Soil moisture retention relates to particle and pore size distribution, bulk density (BD) and carbon (organic matter) concentrations (Hubbard et al. 2013). Soil carbon influences both pore size distribution and moisture retention, with greater carbon concentrations associated with better aggregation, moisture retention and potential for crop production (Hubbard et al. 2013). The concentrations of organic carbon and nitrogen in soils can be a good indicator of soil quality and productivity due to their favourable effects on physical, chemical and biological properties (Bauer and Black 1994; Doran and Parkin 1994). They are a key component of soil eco-system structure and the delivery of multiple ecosystem services (Banwart et al. 2015).

Cover crops can also increase aggregate stability (aggregates retain their integrity under wet conditions) (Bronick and Lal 2005). The extensive fine roots of some crops such as rye enmesh the soil, helping to stabilise aggregates and increase pore size thus improving seedbed structure (Breland 1995). Cover crop impacts on soil aggregation vary with cover crop species, quantity of roots, soil type, and cropping systems (Kaspar and Singer 2011). It was found in a study of six soils in western Australia, legumes were more effective at stabilising soil structure (water stable aggregates) than non-legumes and that lupins were the most effective (Cochrane and Aylmore 1994). It was concluded that particular plant and soil combinations may stabilise some soils and destabilise others (Cochrane and Aylmore 1994). After 25 years of continuous cotton with tillage on a loam soil, when a hairy vetch cover crop was included in the rotation 21.3% of the soil aggregates had diameters of >0.21 mm, compared to 11.8% with common vetch (*V sativa* L.) and 9.5 % for the no cover crop control (Patrick et al. 1957). It was concluded that hairy vetch improved aggregation more than common vetch because it produced more biomass. The hairy vetch treatments also resulted in a lower bulk density, greater porosity and greater water holding capacity in the top 6 cm of soil compared to the no cover control (Patrick et al. 1957).

Soils after a rye cover crop in a sweet corn and green bean rotation was reported to have a greater aggregation and hydraulic conductivity after three years compared to no cover crop (Benoit et al. 1962), cited by (Kaspar and Singer 2011). Interestingly, one treatment involved removing the cover crop shoot material, which demonstrated that the rye roots had a large effect on soil structure. Investigating this further in the sixth year of the study, it was seen that soils with only the rye roots had decreased bulk density, increased capillary porosity and hydraulic conductivity below the plough layer (30 – 37 cm) compared to the no cover control (Benoit et al. 1962) cited by (Kaspar and Singer 2011). The NIAB New Farming Systems 'NFS rotations' study has demonstrated increases in water infiltration from 0.78 mm per minute to 2.19 mm per minute, (measured over a 20 minute period; (Stobart and Morris 2014) with a clover bi-crop approach compared to the standard practice of no cover crop. The authors suggest that these changes relate to the development of a more open soil structure with the use of the clover bi-crop. There were also associated reductions in soil bulk density from 1.17 g/cm^3 to 1.04 g/cm^3 at

20cm depth (Stobart and Morris 2011). In a three year experiment a rye cover crop caused an increase in soil bulk density by 9% and the total pore space by 12% (Haruna and Nkongolo 2015). However, in the third year of the experiment, there was a significant interaction between the cover crop and tillage treatments and under no-till rye caused a 3% reduction in bulk density compared to the no-till control without rye. The authors conclude that interactions between agricultural treatments are complex and their effects on soil physical properties are difficult to predict (Haruna and Nkongolo 2015).

In a field study in Denmark, five years of cover crop treatments increased soil air filled porosity and pore organisation, resulting in the conclusion that the cover crops had created continuous macropores, which improved conditions for water and gas transport and crop root growth (Abdollahi and Munkhlm 2013). It has been shown that daily changes in root diameter loosen and break down compacted soil layers around them (Hamza and Anderson 2005). It was demonstrated, using computer assisted tomography, that radish (*Raphanus*) and Lupin (*Lupinus*) roots exhibit a temporary decrease in diameter after transpiration starts followed by a significant temporary increase (Hamza et al. 2001). This diurnal fluctuation in diameter destabilises soil and loosens any compaction (Hamza and Anderson 2005). Roots of different species and cultivars within species differ in their ability to penetrate strong soil (Singh and Sainju 1998). A study of the effect of soybean on subsurface compaction and root growth found that compaction led to an increase in root growth in the topsoil layer with a decrease in compaction (Rosolem and Takahashi 1998). Some species of cover crops also produce deep tap roots which help break up compacted soil. In pot experiments using hard layers of wax, lucerne was reported to be good at penetrating these hard layers (Löfkist et al. 2005). The same study also identified chicory, lupin and red clover as having intermediate ability to break up compacted soil. In two field trials in Maryland USA, the penetration of compacted soils by forage radish, oilseed rape and rye was evaluated. In the high compaction treatment forage radish had 1.5 and 2 times more roots at 15 – 50 cm depth compared to rye (Chen and Weil 2009). In a different pot experiment using soil with different levels of compaction Rosolem et al. (2002) found that two grasses, guinea sorghum (*S. bicolor*) and pearl millet, (*P.americanum*), were more sensitive to soil compaction than the broad leaved species tested. These authors observed that there seemed to be no relationship between root diameter and root capacity in terms of its effect on root growth in soil with high resistance to penetration (Rosolem et al. 2002). However, creating additional biopores which can be used by subsequent crops will be beneficial, and therefore the number of roots growing through compacted layers will be important (Rosolem et al. 2002). Williams and Weil (2004) observed, at two field sites in Maryland, USA, soybean crop roots growing in the root channels left by the decomposition of cover crop roots. At one site, where drought conditions were more severe and the soil was more compacted, soybean yields were significantly increased following a forage radish and rye mix compared to no cover crop

(Williams and Weil 2004). The authors suggest that the root channels created by the forage radish provided low resistance channels for the soybean crop roots to obtain water stored in the subsoil.

In a 25 year conventional tillage cotton study, cover crops increased soil organic matter, macroposity, mean aggregate size, soil permeability and crop yield (Patrick et al. 1957) cited in (Dabney et al. 2001). In 2005, Bronick and Lal noted that we still need to understand why some cover crops (and cash crops) are more effective at soil structural development than others.

3.5.3. Soil biology and earthworms

The whole soil food web, including both meso and macro fauna, in the soil carry out vital functions, including decomposition of SOM and transformation of nutrients into plant available forms. These 'broad' functions can be delivered by a wide range of organisms (Morris et al. 2014). Soil bacteria and fungi can also contribute to the stabilisation of soil structure by producing extra cellular peptides and enmeshing filaments. Where soil processes are delivered by a more limited group of organisms (e.g. the nitrification of ammonium-N to nitrate-N, symbiotic nitrogen fixation or mycorrhizal associations) they are more affected by adverse soil conditions and scarce food resources (Powlson et al. 2011).

Cover crops may support microbial communities of bacteria, non-pathogenic *Fusarium* species, Streptomyces and other actinomycetes as part of a diverse microbial community, which may function to suppress pathogens through competition, antibiosis, parasitism or by inducing systemic resistance in plants (Hoitink and Boehm 1999; Rayns and Rosenfeld 2006). Allowing cover crops which support mycorrhiza to grow until three weeks prior to planting of the following cash crop was reported to encourage mycorrhizal fungal associations to the benefit of subsequent crops without increasing the risk of crop disease (Dabney et al. 2001). Cover crops may also provide a bridge between mycorrhizal crops in order to maintain a high population of soil mycorrhiza (Rayns and Rosenfeld 2006). Legumes are reported to increase mycorrhizal fungi more than other cover crops (Morris et al. 2014).

Bacterial and fungal products and fungal hyphae provide the glue to form stable micro aggregates (Tang et al. 2011; Watts et al. 2005). Arbuscular mycorrhizal fungi produce glomalin (Hoorman et al. 2011), and it has been reported that there is a positive linear relationship between the amount of glomalin and the stability of soil aggregates (Wright and Upadhyaya 1998). Ten years of incorporation of the legume horsegram (*Macrotyloma uniflorum*) in a sorghum and sunflower rotation in India increased microbial biomass by 28% compared to fallow (Venkateswarlu et al. 2007). The fluorescein diacetate hydrolytic activity (FDA) assay is a measure of soil enzyme esterase and is used as an indicator of microbial activity and biomass (Kaspar and Singer 2011). After three years with crimson clover or rye cover crops soil had a greater total FDA compared to soil without a cover crop (Reddy et al. 2003). Crimson clover had a greater stimulatory effect on soil biology than rye, which the authors suggest may be due to its lower C:N ratio, meaning that it had more readily available amino acids and carbohydrates than the grass crop.

Large soil fauna, particularly earthworms, mix soils and form channels within the soil matrix. These channels assist water infiltration and provide access for roots (Morris et al. 2014). In a study in the 2014/15 season, using a range of different cover crop species as mixes or single species across 4 sites, the farm standard cultivated area or an area left to stubble had fewer worms compared to the cover cropped areas, with reductions of between 25% and 37% (Stobart et al. 2015). It should be noted that earthworm movement between areas of the fields and between plots cannot be ruled out, but there have been other studies showing similar improvements in earthworm numbers (Stobart et al. 2015). In a study using food choice chambers and litter bags under field conditions ryegrass residues were the preferred food resource of the earthworm (*Lumbricus terrestris* L.) over mustard, phacelia or rapeseed residues and these were in turn preferred to oats (Valckx et al. 2011). It is interesting to note that living oats were avoided in comparison to habitats with bare soil or yellow mustard plants (Valckx et al. 2011). After eight years of a rye cover crop, soils had 33.3 worms m^{-2} compared with 12.8 worms m^{-2} without rye treatment (Reedler et al. 2006). It was suggested that the earthworm populations were higher in the rye treatment due to increased availability of water. Reedler et al (2006) also found the populations of microarthropods were higher with rye cover crop treatment, but that there was no difference in the population of soil fungi assessed.

Main Points

- The effect of cover crops on the total SOM or SOC content of a soil is highly variable and difficult to detect. A number of studies have reported no change in SOM or SOC, whereas other studies have reported increases in SOM ranging from 0.3% up to 42% relative to treatments without a cover crop. Importantly, no study reported a decline in SOM.
- Measures of soil organic matter fractions (free light fraction (FLF), intra-aggregate ight fraction (IALF) and heavy fraction) (HF) may be a more sensitive indicator of change.
- The roots of (cover) crops create biopores and can break up compacted soil layers, which can improve subsequent crop root growth.
- Crops with a low C:N ratio break down more quickly and will have less of a long term effect on SOM.

- Cover crops may provide a bridge for mycorrhizal fungi and can support soil microbial communities and increase microbial biomass.
- There is some evidence to indicate that cover crops can increase earthworm populations.

3.6. Cover crops as forage

It is possible to destroy cover crops mechanically or by livestock grazing. Benefits from cycling N, P, K and other nutrients in cover crops through ruminant livestock such as sheep or cattle could make some nutrients more available to the following crop, compared with mechanical incorporation of an over wintered cover crop and its decomposition in the soil, In Manitoba, Canada, on a fine sandy loam in an extreme continental climate and on a long-term organically managed farm, a pea and oat mixed cover crop was established in May/June, grazed in July with an equivalent of 1111–1667 sheep days per hectare for 24 hours. The remaining plant and sheep manures and the cover crops in control ungrazed plots were then incorporated in July, and spring wheat drilled the following April/May. It was found that grazed plots had significantly greater nitrate availability in the soil, and greater N uptake in the following spring crop in some years, but no difference in P or K availability or spring crop yield compared to ungrazed plots (Cicek et al. 2014b). In the same farm system, with a variety of cover crops including pea/oat mixtures and straight legumes, spring wheat grain yields were not significantly improved by grazing off the preceding cover crop, but the spring crop had a higher nitrogen uptake after grazed (107 kg N/ha) than after ungrazed cover crops (98 kg N/ ha, Cicek *et al.* 2015). However this system is not necessarily representative of an overwinter cover crop being grazed all winter and incorporated in spring and was not conducted in the mild UK climate. There are some agronomic problems which could occur in certain situations when grazing over winter cover crops, such as uneven deposition of excreta, risks of soil compaction and leaching of N deposited in urine (Stout 2003).

There have been a number of studies on the agronomic and ecological impacts of grazing short term winter cover crops on the remaining arable crops in the rotation in the warm and humid south eastern USA, reviewed by Sulc and Franzluebbers (2014). No soil compaction was observed in an over winter cover crop grazed with 2430 kg live cattle/ha, however following crop yield responses were variable (Sulc and Franzluebbers 2014). Total soil N on a sandy loam soil in Georgia, USA was not significantly increased by cover crop grazing compared to ungrazed cover crops. In the north east and mid-west USA, which is cool and humid, winter rye or triticale cover crops are sown after harvest of wheat, soybeans or maize and grazed during winter. In this system, penetration resistance was increased by grazing of cover crops and grain maize yield was increased by 6% in grazed plots (Maughan et al. 2009; Sulc and Franzluebbers 2014).

In Europe, there have been fewer studies on grazing of short term cover crops. Grazing of stubble turnips, a species which could be used as a winter cover crop, on the calcareous soils of the Cotswolds in the UK resulted in significant N leaching (Allingham et al. 2002). In France, some work has been done on developing farming systems for growing millet or sorghum as spring cover crops or ryegrass as over winter cover crops to be grazed (Huchon et al. 2010; Meslier et al. 2014).

Addition of livestock and their manures to a cover crop system could also have an effect on the wider ecosystem of the farm, and especially insect life. However there was no significant difference in weed or carabid beetle communities in a June-sown mixed cover crop (buckwheat, beet, peas and sweet clover) destroyed by mowing or destroyed by sheep-grazing the following August in Montana (McKenzie et al. 2016).

Main Points

- Limited research shows no clear effect on availability of nutrients as a result of cover crop destruction by grazing

3.7. Effects on biodiversity and habitat provision

There is evidence that increasing the diversity of vegetation in arable ecosystems either through permanent managed uncropped land or temporary cover crops could increase species biodiversity by providing a greater range of habitat and food in intensive arable systems (Landis et al. 2000). The value of uncropped land on arable farms to bird and invertebrate biodiversity has been demonstrated in the UK by Henderson *et al.* (2012) and Storkey *et al.* (2013), who found a positive correlation between a high diversity of plant species and traits found in the arable environment and a high diversity of invertebrate communities, which is beneficial for insect-eating farmland birds. Grasses can act as habitats for overwintering generalist predators, especially carabid and staphalinid beetles (Collins et al. 2003; Kajak and Lukasiewicz 1994; Rayns and Rosenfeld 2006). It was reported that Tussocky grasses such as cocksfoot or tall oat grass are the most effective species acting as overwintering habitats (Collins et al. 2003). Cover crops are a valid way to increase arable vegetation diversity for the portion of the season, though there could be further benefits to biodiversity from managed perennial uncropped land which may not be realised by annual cover crops (Tschumi et al. 2016).

Biodiversity increases can also benefit crop yield, as more diverse vegetation can increase the abundance of natural enemies of crop pests. In South Dakota, an over winter grass (*Elymus trachycaulus*) cover crop had a negative impact on the life cycle of the maize insect pest *Diabrotica virgifera* compared to an over winter fallow treatment in a no-till system (Lundgren and Fergen 2010). Lundgren and Fergen (2010) suggested this was due to a greater natural enemy population in the cover cropped treatment.

Main points

- Cover crops are likely to increase farmland biodiversity by providing a greater selection of habitats, depending on the cover crop management, but no systems studies have proven this.

4. Cover crop agronomy

4.1.1. Common cover crop choices

Different cover crops have contrasting properties, so it is essential to select an appropriate cover crop or species mix suited to the system and objectives. Cover crop choice needs to fit with farm practice, capabilities, expertise, budget and available equipment. While single species can be used as cover crops, species mixtures are a commonly used approach. Components of a species mixture can be selected to deliver different benefits and complementarities (Döring et al. 2013); mixtures also provide some risk management, as one species may do well when another does not. AHDB information sheet 41 (Opportunities for cover crops in conventional arable rotations) summaries some of the materials and types used commonly in cover cropping and presents a useful outline (Table 5). Further detail on specific species, types and seed rates that might be used within cover cropping approaches is also presented in Table 66 (based on (Stobart 2015; Döring et al. 2013; Rosenfield and Raynes 2011). Further UK based agronomic and species information on a range of cover crops and mixes can be found in Stobart 2015; Döring et al. 2013; and Rosenfield and Raynes 2011.

Table 5 Agronomic benefits, characteristics and considerations for commonly use cover crop material (AHDB information sheet 41)

	Brassicas	**Legumes**	**Grasses and cereals**
Example species	**Mustards, radishes, turnips**	**Vetch, clovers**	**Oat, rye, rye-grass**
Benefits	Brassicas can grow rapidly in the autumn. There is a good understanding of brassica agronomy (from oilseed rape experience) and establishment systems tend to fit with farm equipment.	Legumes fix nitrogen, which can benefit following crops and raise fertility. The amount of nitrogen fixed depends on species, growth and temperature but is likely to be small with an overwinter cover crop.	Cereals and grasses can deliver good early ground cover (important where erosion is a concern) as well as other benefits, including vigorous rooting.
Characteristics	While there are many types and growth habits, autumn-sown brassicas often provide good ground cover and deep rooting. This can mitigate leaching risks and improve soil structure. Some have trap crop and biofumigant activity.	In addition to nitrogen fixing, like most cover crops, legume roots can help to improve soil structure; rooting will vary depending on species, field conditions and cover crop duration.	For autumn sowing, these species can establish quickly and some types offer a wider range of sowing timings than brassicas or legumes.
Sowing	They are often late summer-sown or early autumn-sown at similar timings to oilseed rape. Fields conditions and variety should guide specific sowing dates	Legumes tend to be slower growing than brassicas and, for autumn use, often need to be sown earlier (late July-August) to aid growth and promote nitrogen fixation.	Sowing times vary with species and may range from July through to September.

Considerations	Good autumn establishment is critical to maximise growth, particularly where soil structure or nitrogen capture are key objective. Consider potential rotational conflicts, e.g. clubroot, where vegetable brassicas or oilseed rape are grown in the rotation.	Consider management around the sowing and establishment of small-seeded legumes (used alone or in mixtures). There are also potential rotational conflicts, especially where other pulses and legumes are grown in the rotation.	Management tends to be similar to autumn cereals and grasses. They act as a green bridge for cereal pests and diseases.

Table 6 Summary information on a range of options that may be used as cover crops*

Cover crop	Crop type	Sowing (autumn)	Example sowing rates kg/ha (as single species)	Main uses/comment
Brassicas				
Mustard	Broadleaf (brassica)	Mid Aug – mid Sept	5-15	Competitive crop with benefits for soil around management of erosion, leaching and structure. Consider rotational conflict with oilseed rape.
Oilseed rape (OSR)	Broadleaf (brassica)	Mid Aug – mid Sept	5-15	Competitive crop with benefits for soil around management of erosion, leaching and structure. Consider rotational conflict with oilseed rape.
Radish	Broadleaf (brassica)	Mid Aug – early Sept	4-12	Competitive crop with benefits for soil around management of erosion, leaching and structure. Consider rotational conflict with oilseed rape.
Legumes				
Beans	Broadleaf (pulse)	Late Aug – Sept	100-200	Mainly used in fertility building as part of mixtures or single species. Better suited to later sowing than many legumes, but consider rotational conflicts.
Black medic	Broadleaf (legume)	August	8-10	Mainly used in fertility building mixes, faster growing than some clovers, and can improve soil structure. Consider rotational conflict with pulses.
Crimson clover	Broadleaf (legume)	August	10-15	Mainly used in fertility building mixes, faster growing than some other clovers, and can improve soil structure. Consider rotational conflict with pulses.
Lucerne	Broadleaf (legume)	August	20	Mainly used in fertility building mixes and can be better suited to droughty soils than some other legumes. Consider rotational conflict with pulses.
Peas	Broadleaf (pulse)	Late Aug – mid Sept	200-400	Mainly used in fertility building as part of mixtures or single species. Better suited to later sowing than many legumes, but consider rotational conflicts.
Sanfoin	Broadleaf (legume)	August	70	Mainly used in fertility building and grazing mixes but is less well suited to droughty soils than some other legumes. Consider rotational conflict with pulses.
Sweet clover	Broadleaf (legume)	August	10-15	Mainly used in fertility building mixes, quite slow growing but can improve soil structure (from longer residence). Consider rotational conflict with pulses.

Vetch	Broadleaf (legume)	August - Sept	80	Quite a competitive legume and mainly fertility building mixes and can be later sown than some other legumes. Consider rotational conflict with pulses.
White clover	Broadleaf (legume)	August	10-15	Mainly used in fertility building mixes, quit slow growing but can improve soil structure (from longer residence). Consider rotational conflict with pulses.
Cereals & Grasses				
Oats & Rye	Grass (cereal)	Mid Aug – mid Sept	30-100	Competitive crop with benefits around shallower soil management, leaching reduction and erosion mitigation. The sowing will depend on specific use.
Ryegrass	Grass (Lolium)	Typically August - Sept	30-35	Competitive crop with benefits around shallower soil management, leaching reduction and erosion mitigation.
Other				
Buckwheat	Broadleaf (polygonum)	August	70	Used around fertility building and particularly scavenging phosphorus. Buckwheat is not frost tolerant and is probably best used in mixtures.
Chicory	Broadleaf (Asteraceae)	August	15	Deep rooted cover crop (delivering soil structure benefits) better suited to longer term use especially where grazing is of interest. Can be used in mixtures.
Phacelia	Broadleaf (boraginacae)	Mid Aug – mid Sept	c. 10	Competitive crop with benefits for soil around management of erosion, leaching and structure. Not entirely frost tolerant but unlikely to senesce fully over winter.

* based on Stobart (2015), Rosenfield and Raynes, (2011) and informal grower feedback collated through grower groups and field meetings.

4.1.2. Common cover crop objectives and selection criteria

On farm, four of the main reasons for adoption/use of cover crops are as follows.

- Soil fertility improvements: a range of cover crops can be used as green manures to add organic material to the soil. In addition, legume species can fix nitrogen which can also help to augment site fertility.
- Soil structure benefits: cover crops can deliver improvement to soil structure at a range of depths (although it is important to know where the restriction is that is being addressed and the nature of the impediment). In addition, improved structure can enhance the ability of roots to explore the profile and access nutrients.
- Managing weeds and pests: cover crops can provide a trap crop environment to reduce seed banks or outcompete weeds (or potentially show allelopathic effects) to help to provide a clean seedbed for following crops. Some can provide wider trap crop activity (e.g. for pests) and certain brassica species can act as biofumigants.
- Environmental management: for example where cover crop mixtures (e.g. oats and brassicas among others) provide rapid autumn ground cover may be a useful simple tool to help mitigate erosion or reduce nitrate leaching and diffuse pollution risks. In addition, cover crops can often provide additional habitat and cover.

An appraisal of the scientific literature around the potential benefits and impacts of cover crop use is presented elsewhere in this review, however within these main selection criteria understanding which cover crops to use is highly important. Specimen cover crop selection strategy keys, based on (Stobart 2015), are set out in the following section (Table 77, Table 88 and Table 99).

Table 7 Selecting cover crops for the management of soil fertility, adapted from Stobart (2015)

Goal: **Green manure**	**Nitrogen (N)**	**Phosphate (P)**	**Other nutrients**
Range of cover crop types are suitable as ‘green manures’ to add organic material to the soil.	A range of legume species can be used as cover crops. They have the potential to fix N and in many cases also improve soil structure.	Potential from some polygonums e.g. buckwheat (P scavengers) and legumes (with cluster rooting or proteoid roots, which are clusters of closely spaced short lateral rootlets).	Cover crops with active rooting can potentially help mine and cycle nutrients.
Species giving good autumn growth and ground cover; for example oats, phacelia and brassicas (such as mustard or radish). Some (faster growing) legumes may also be suitable; especially if they have opportunity for nitrogen fixing. Consideration needs to be given to the management of large amounts of biomass from rapid growth.	A range of species may be used. Including trefoil, clovers (e.g. crimson clover), vetch and Lucerne. . Early autumn legume sowing is needed to maximise the opportunity for legumes to fix nitrogen.	Buckwheat (Knox et al. 2010) and lupins (Kamh 1999) are possible options for the acquisition of P. Lupins typically need pH <7 and buckwheat is not frost tolerant. Mycorrhizal associations may also be of benefit for P acquisition (Smith 2003). The relationships do not form with brassicas.	Consider species with extensive root systems or mixtures with complementary rooting (e.g. deep and shallow). There is little published UK research in this area and further field information is needed.
Soil organic matter (section 3.5.1)	Nitrogen uptake and release (Section 3.1	The review does not cover phosphorous and other nutrient cycling in detail	

Table 8 Selecting cover crops for soil structure, adapted from (Stobart 2015)

Period for cover cropping: Autumn (to be followed by a spring crop)			Spring			Full season fallow		
Where is the main / targeted structural impediment?								
Shallow (c. 0-20cm)	*Deep (c. 20-40cm)*	*Very deep (> 40cm)*	*Shallow (c. 0-20cm)*	*Deep (c. 20-40cm)*	*Very deep (> 40cm)*	*Shallow (c. 0-20cm)*	*Deep (c. 20-40cm)*	*Very deep (> 40cm)*
Range of suitable types including cereals, brassicas, legumes and other broadleaf species.	Brassica cover crops (and possibly other deep rooted broadleaf cover crops).	Short duration cover crops are not well suited to this scenario.	Range of suitable types including cereals, brassicas, legumes and other broadleaf species.	Brassica cover crops (and possibly other deep rooted broadleaf cover crops).	Short duration cover crops are not well suited to this scenario.	Range of suitable types including cereals, brassicas, legumes and other broadleaf species.	Brassica cover crops and some legume species.	Potentially brassica and certain legume species (e.g. lucerne or sweet clover).
Example options and/or comments								
Oats, phacelia and brassicas (such as mustard or radish), but consider use of mixtures with complementary rooting depths.	Brassica are potentially useful (e.g. radish types), but consider use of mixtures particularly if other depths are of interest.	None; timeframe is typically too short.	Cereals, legumes (e.g. trefoil, vetch) and broadleaf crops (e.g. phacelia or brassicas); consider mixes with complementary rooting depths.	Brassica are potentially useful at these depths (e.g. radish), but consider use of mixtures particularly if other depths are of interest.	None; timeframe is typically too short.	Oats, phacelia and brassicas (such as mustard or radish); potentially in mixes. In addition legumes (such as trefoil or crimson clover), give opportunity N fixing in spring.	Mustard, radish or possibly some clovers or other deep rooted species	While research suggests this approach has potential, there is little UK field data in this area.

Related review sections
Soil physical properties & structure (Section 3.5.2)

Table 9 Selecting cover crops for the management of weeds and pests, adapted from Stobart (2015).

	Weeds and pests: key to select a suitable cover crop/mix component.				
Goal: **Managing weed populations (weeds)**		**Sanitising cover crops (weeds and pests)**		**Other biological routes (weeds and pests)**	
Trap crops (weeds)	Crop competition	Bio-fumigation	Trap crops (pests)	Allelopathic effects	Habitat creation (pests)
A cover crop that facilitates weed establishment and is then destroyed before the weed can produce viable seed.	Cover crops that outcompete weeds may help to provide a clean seedbed for the following crop.	Some brassica species have high levels of soil sterilising chemicals (such as isothiocanate). Such cover crops might be used against weeds and soil pests within a wider management strategy.	Some cover crops can promote egg hatch in some pest species. This can be effective against certain nematode types, e.g. sticky nightshade (*Solanum sisymbriifolium*) for potato cyst nematodes ((Scholte and Voz 2000))	Some cover crops (e.g. clovers, rye and oats) can have allelopathic activity; inhibiting the germination of weed and other species.	Pest management can also be delivered through improving predator habitat.
	Example options and/or comments				
A wide range of cover crops can be used for this purpose. Mixtures are common and components could include brassicas cereals or legumes.	Brassica species (e.g. radish and mustards) that can cover the ground are common; but a range of cover crops could be used.	Choose a specific variety (usually radish or mustard) that is sold for this activity. Production, destruction and incorporation are important in gaining efficacy from such approaches.	Select a variety sold for this activity. Production, destruction and incorporation are important in gaining efficacy from such approaches.	Limited current UK field information and further research is needed in this area.	Potential to use cover crops strategically on farm to provide habitat or companion crops for wide row species. Limited current UK field information and further

Cover crops need to be open enough for weed germination.	Cover needs to be uniform and soil disturbance generally needs to be minimised when establishing following crops for benefits to accrue.				research is needed in this area.
	Related review sections				
Weed suppression - Allelopathic effects & physical competition (section 3.2)		Biofumigation effects (section 3.3)			Weed suppression - Allelopathic effects & physical competition (section 3.2)

Practical cover crop management and inputs.

4.1.3. Cover crop establishment methods

The establishment technique deployed will depend upon a number of considerations including cover crop species, soil type, site, weather conditions and which crop the cover crop is following (Table 1010). For example, establishing a cover crop after late harvested crops (e.g. maize) is most likely only to be suitable on light/medium soils (Newell-Price et al. 2015). However, in most situations following early harvested combinable crops, a cover crop can be drilled or broadcast followed by seedbed consolidation (Stobart 2015).

Table 10 Establishment options for cover crops depending on previous cropping and soil type before the establishment of spring crops (Adapted from Newell-Price et al 2015)

Previous cropping	Soil type	
	Light / medium	Heavy
Cover crop following early harvested combinable crops	Light cultivation followed by broadcasting or drilling and rolling in late summer / early autumn	Establishment method more challenging due to smaller window of opportunity for light cultivations and drilling seed in autumn
Cover crop following late harvested crops	Over-sown into maize crop, once maize is fully established ((6-8 leaf stage) or, in a dry autumn, it may be possible to establish a cereal (e.g. rye) or brassica cover crop after late harvested crops (e.g. sugar beet, potatoes and field vegetables)	Not suited to heavy soil types

The success of a cover crop will depend upon time of sowing, and to a lesser degree, method of establishment and the success with cover crops will depend upon the attention to detail, e.g. managing the cover crop as you would a main cash crop. Primarily cover crops should be established in good time particularly in situations where soil conditions are favourable (warm and moist soils) to achieve good root establishment and top growth before cooler temperatures slow growth.

Later sown cover crops will have less time to develop before crop destruction and will not accrue sufficient biomass to provide adequate soil protection or enhance soil quality (Balkcom et al. 2012). Within the Kellogg’s Origins initiative, farmers have been involved with a unique large-scale participatory programme examining the use of cover crops on farm. Across a range of farm locations, cover crop species and drilling parameters, there was a strong relationship between sowing date and autumn growth (Figure 2); with earlier sowing promoting greater cover crop growth (Stobart et al. 2015).

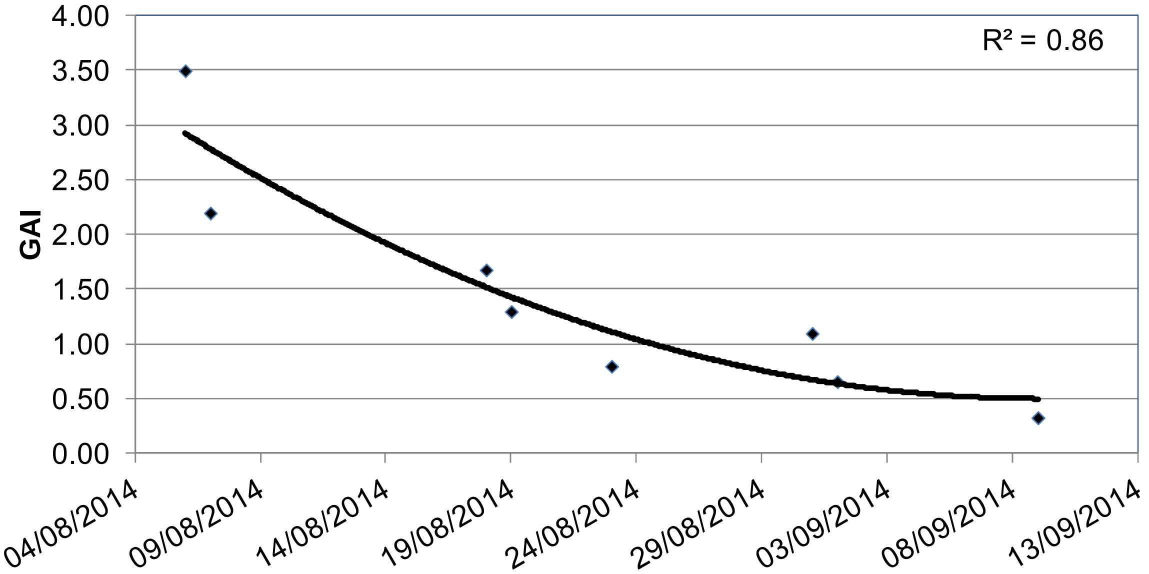

Figure 2 The impact of sowing date on mean autumn cover crop (mean of a range of species) green area index (GAI) over eight sites in October 2014 (Stobart et al. 2015)

Cover crops can typically be established by either broadcasting the seed or by drilling the seed. Good seed-soil contact is required for germination and emergence. The most effective establishment methods depend upon soil and weather conditions at the time of drilling. Establishment methods vary in their cost; establishment by broadcasting and rolling tends to be cheaper, but can be more variable and seed distribution uniformity should be considered (Stobart 2015). Typical costs associated with the establishment of cover crops are shown in Table 1. Whilst under-sowing can be a low cost establishment technique it often results in compromised yield of the main crop or poor establishment of the cover crop (Newell-Price et al. 2015).

Table 11 Typical establishment costs for cover crops † (Stobart 2015).

Establishment approach	Typical cost (£/ha)
Broadcasting / direct drilling	15-30
Combi-drilled systems	>40

† – The costs above do not account for the cost of the cover crop seed which can typically vary from £15-60/ha.

Most small seed species (e.g. some smaller seeded legumes including clover) require shallow placement (typically 5 mm deep), whilst larger seeded species (e.g. larger seeded legumes including vetch) and cereals can be sown at 30 mm to 50 mm deep. To ensure crop residues are evenly distributed and to create some surface tilth a shallow cultivation or straw rake may be used to provide uniform seeding depth and adequate seed-soil contact (Balkcom et al. 2012). When drilling seed mixes, a range of drill types can be used; single pass systems are often adopted to improve timeliness and reduce cost. When using seed mixes (often including different species and seed size) consideration should also be given to row width and seed spread and the risk of the seed ‘settling out’ in the seed hopper that can result in uneven species distribution across the field.

Broadcasting cover crops tends to work better for smaller seeded species than larger seeded species and can be successful on light and medium soil types. For example, research within the New Farming Systems research programme at Morley, Norfolk on a sandy loam soil has investigated the use of a brassica species, fodder radish (*Raphinus sativus*), that has been typically broadcast onto a lightly cultivated soil (typically shallow disced or straw raked) in late August or early September resulting in good crop establishment (Stobart and Morris 2013). However, in situations where seed-soil contact may be more difficult to achieve (e.g. on heavy clay soils) then drilling the seed is likely to achieve better establishment compared to broadcasting but will likely add to costs. In most situations, rolling the seedbed after broadcasting or drilling of the cover crop (apart from where soil conditions are too wet) will improve crop establishment. Research in Denmark reported that there was little effect of tillage (direct drilling, harrowing or ploughing) on the cover crop dry matter yields or N uptake, but there was a tendency for N uptake to be higher in ploughed soil (Munkholm and Hansen 2012). In the following spring barley crop, yields following the cover crops tended to be higher after ploughing although this was only significant in one year (out of the two year study).

Recent research by Stobart et al 2015 on a loamy soil over clay comparing establishment of a range of cover crops with two different methods (conventional drilling system - tined cultivator followed by a disc drill) compared to a single pass (disc drill) approach suggested that there was relatively little difference in cover crop populations (Table 42). However, there was some suggestion that conventional drilling resulted in larger cover crop canopies, but that single pass drilling resulted in reduced spring weed populations due to the degree of soil disturbance (Stobart and Gosling 2015). Research by Stobart et al. (2015) reinforced the importance of cover crop drilling date over other parameters (such as cultivation approach) to deliver adequate levels of autumn growth. Further research to examine how establishment system and other crop management (e.g. starter fertiliser) affect cover crop establishment would be beneficial.

Table 42 Comparison of conventional or single pass drilling approaches for cover crop establishment on a single site in the Kellogg's Origins programme (Stobart et al. 2015).

	Autumn assessment			*Spring assessment*		
	Cover crop		Weed	Cover crop		Weed
Drill type	Count number/m^2)	GAI	Count (Number/m^2)	Count (Number/m^2)	GAI	Count (Number/m^2)
Single pass drilling	42	1.0	44	19	1.4	27
Conventional drilling	57	1.3	48	18	1.3	43

4.1.4. Starter fertiliser

There is currently little impartial information to guide on farm practice for starter fertiliser use in cover crops or for gauging nutrient release for the benefit of the following crop. For example there is no current inclusion of fertiliser recommendations for starter fertiliser on cover crops in RB209 (Anon 2010). With regard to nutrient uptake and release by cover crops RB209 does note that '*Following destruction of the cover crop, this nitrogen [captured] will be gradually mineralised over many years. However, the amount becoming available for uptake by the next crop is relatively small and difficult to predict. Where cover crops have been used regularly, soil analysis can be a useful technique to help estimate the overall supply of soil mineral nitrogen'*. UK field research examining starter fertiliser use on cover crops is limited. Recent research within the Wensum Demonstration Test Catchment project (Lovett et al. 2015) indicated a 15% increase in the canopy size for an autumn sown brassica cover crop from the application of 30kg/ha N starter fertiliser, but also noted that this had no associated impact on root growth (a small numerical decrease in root growth of around 5% was noted). Wider UK farm based cover crop research by Stobart et al. (2015) compared 20-40 kg/ha N starter fertiliser over a range of 15 cover crop approaches (single species and mixtures) across two sites; while some variation between site and cover crop approach was apparent, mean data again suggest a c. 15% increase in cover crop biomass with starter fertiliser application and an associated mean doubling of autumn weed populations (this was potentially associated with the increased site fertility). This research also suggested that establishment date had a greater impact on early season cover crop growth than starter fertiliser but also that the interaction between sowing date, cover crop type and starter fertiliser use should be examined further. These findings on early season N use in cover crops are in keeping with earlier UK data, such as that of (Richards et al. 1996), who concluded from UK studies, that sowing date had a greater bearing on cover crop growth than early season N availability.

4.1.5. Pest management

While the provision of cover by cover crops provides valuable wildlife habitat (Snapp et al. 2005), (Stobart 2015) suggests that monitoring autumn sown cover crops for pest damage is required;

noting that while there is often no input requirement, in some situations pest protection could be needed for grazing by pigeons, slugs or insect pests. Cropping, soil management and cover crop practice may all influence soil borne pests (Katan 2000) and natural enemy populations (Holland and Luff 2000). Slugs are often cited as a key grower concern associated with cover crop use. However, research suggests that their impact on slug populations may be quite scenario specific. For example slugs exhibit preferences for different plant species (Briner 1988). There have been instances of increased slug populations in cash crops as the result of a grass cover crop (Frank 1998). Rayns and Rosenfield (2003) reported the results of a trial carried out at a single site investigating the effect of different fertility building crops on slug populations (Anon 2002). The work recommended that for short term cover crops grown to prevent nutrient leaching, ryegrass resulted in less severe slug problems compared to legumes such as clover or vetch. In the case of legumes, Lucerne resulted in slower slug population growth compared to other legumes tested (Anon 2002). Consequently cover crops may decrease slug numbers if they are unpalatable to the pest although the reverse may occur if they create favourable environmental conditions for the pest (Jordan and Hutcheon 1996); (Mangan et al. 1995).

Some cover crops can also act as biofumigants (see section Biofumigation effects) and Frost et al. (2002) demonstrated that a biofumigant mustard cover crop has potential to reduce slugs prior to planting potatoes. Economic issues with using cover crops for biofumigation at the field scale include choosing the correct species to target the pest, achieving thorough maceration of cover crop to ensure high levels of biofumigant compounds are produced, timing of incorporation, and having enough biomass (summer grown cover crops would have more biomass than winter grown) and therefore enough material to produce biofumigant chemicals at an effective concentration in the soil.

The wider interaction of cover crop, primary cultivation practice and slug predators also needs consideration, as beetles are vulnerable to intensive tillage (Symondson et al. 1996). Some beetle species actively search for slugs (Bohan et al. 2000) and large polyphagous beetles, such as *Pterostichus melanarius* are known to feed on them; studies have shown c.84% eating slugs (Symondson et al. 1996), with a preference for small slugs (McKemey et al. 2001). Densities of the slug predating species can reach 80-90 m^2 (Holland et al. 2007), but are reduced by intensive cultivations, especially in spring (Holland and Reynolds 2003) and tend to be higher with minimum tillage and residue incorporation (Symondson et al. 1996). The balance between the risks posed to cover crops and following crops from slugs and other pests, and the potentially beneficial predator habitat afforded by cover crops is not well understood; but it appears likely that this balance could be manipulated through selection of cover crop species and production system components. From a practical perspective, field studies by Silgram et al. (2015), with rye and brassica based cover crops ahead of potatoes, did not demonstrate any problems with slugs or other pests, and supported earlier work (Welland et al. 1996), using phacelia and rye cover crops in vegetable based cropping systems.

4.1.6. Cover crop destruction

The interaction of soil type, cover crop growth (canopy size and type of growth) and sowing system (e.g. drill type) will have a bearing on the method of destruction. In general, options and opportunities are more extensive on light to medium soils, whereas on heavier soils thought should be given to opening up cover crops early enough to allow the soil surface to dry out (the biomass of the cover crop can act as a blanket reducing any natural drying process) ahead of drilling (Stobart 2015).

The best approach to use is likely to be highly farm specific. The timing of cover crop destruction has been shown to affect soil temperature, soil moisture, nutrient cycling, tillage and drilling operations of the following crop and potential impact of allelopathic compounds on the following crop establishment (Clark 2012; Balkcom et al. 2012; Bronick and Lal 2005). Due to the many factors involved, decisions about when to destroy the cover crop must be site and situation specific (Balkcom et al. 2012). There are a number of advantages of destroying a cover crop early rather than late including:

- Increasing the rate of soil warming
- Reducing the potential phytotoxic effects of residues on the following crop
- Reducing survival of disease inoculum
- Speeding decomposition of crop residues, decreasing the potential interference with the following drilling operations

Research from cover crop trials in USA, has suggested as a general rule, cover crops are destroyed two to three weeks ahead of drilling the following crop to ensure that the plant material is dry and brittle which allows for tillage and drilling equipment to cut through the residue easily (Balkcom et al. 2012). Cover crops are most commonly destroyed using non-selective herbicides which also ensure destruction of weed species that have germinated during the period that the cover crop has been in the ground. There is some concern that over the use of herbicides to destroy cover crops may increase the risk of the development of herbicide resistance. In the USA, the over reliance on glyphosate for weed control in fallows and Roundup Ready (RR) crops, especially cotton and soybeans, has led to the development of resistance (Blatchford 2012). (Stobart 2015) suggested that autumn-established cover crops can be killed off by frost, grazed, destroyed mechanically or sprayed with herbicides early in the year (while other herbicides could be used glyphosate tends to be the most commonly used). Difficulties with ‘destroying’ the cover crop can have implications for establishment of the following spring crop, although crops such as buckwheat (*Fagopyrum esculentum*) are not frost hardy and so decompose relatively quickly

(Newell-Price et al. 2015). Munkholm and Hansen (2012) reported that, where ryegrass or dyers woad were killed by glyphosate in early April the residues of the cover crops made establishment of the spring barley difficult. However, they suggested that this may have been avoided if the cover crop had been destroyed earlier in the season (late autumn or early winter).

While findings have demonstrated that a range of approaches can be used successfully for cover crop establishment and destruction, currently there is little published literature on methods to optimise combinations and approaches for the destruction of specific cover crops and the establishment of the following crop for UK conditions and farming systems (e.g. crop rotations). Therefore, it is recommended that further experimental research using structured, replicated field trials are undertaken across the UK in differing cropping systems and soil types to develop better guidance for growers on the approaches most suited to specific scenarios.

5. Economics and Decision Making

5.1.1. Yield and economic responses:

An evaluation of the scientific literature on the effects, impacts and responses from cover crops are given elsewhere in this review. However, in the context of practical adoption in the rotation, yield and gross margin benefits achieved in the UK are going to be of direct interest to growers. Cover crop use has grown substantially over recent years (Green 2015) and remains a developing area for research. There are relatively few published UK studies with detailed yield and economic appraisal using data over multiple seasons and sites.

Research work undertaken by NIAB TAG, within the National Agronomy Centre (NAC) initiative examined over a four year period (over harvest years 2009 to 2012; Stobart and Morris personal communication) the use of a short term autumn legume mix (black-medic/trefoil - *Medicago lupulina*) sown in August and destroyed in January/February before the establishment of spring barley. The research considered the interaction of cover crop use and N dose on the following spring crop; a summary of yield responses extracted from NIAB NAC reports are presented in Table 53. Mean cross season yield responses from the use of the cover crop were observed both where no further N inputs were used on the following spring barley crop (c. 0.8 t/ha) and where an N dose of 150 kg/ha N was used on the following spring barley crop (c. 0.3 t/ha). It was proposed in the reports that weather, field conditions and cover crop growth all had an impact on the response in any given season.

Further research on a spring oat crop following autumn cover crops at Loddington (Leicestershire; (Stobart et al. 2016)) demonstrated improved soil structure characteristics (measured through the VESS system; (Guimarães et al. 2011)) from the use of cover crops compared to undisturbed stubble (similar improvement to that delivered by an autumn cultivation). The research also assessed mean yield responses in the direct drilled spring oat crop following the cover crop; a mean increase of c. 0.5 t/ha was recorded following cover crop use compared to the stubble area (and c. 0.25t/ha compared to the autumn ‘farm standard’ cultivation).

Table 53. Yield response (t/ha) in spring barley receiving a specified nitrogen dose (kg/ha) following an autumn black medic cover crop use in NIAB TAG studies 2009-2012.

Spring barley yield (t/ha)					
	2009	2010	2011	2012	**Mean**
0 kg/ha N (- cover crop)	2.56	3.61	3.07	4.07	**3.33**
0 kg/ha N (+ cover crop)	4.01	3.52	3.13	5.96	**4.16**
150 kg/ha N (- cover crop)	5.76	5.40	3.62	6.50	**5.32**
150 kg/ha N (+ cover crop)	6.31	5.58	3.74	6.78	**5.60**

Similar work by Shah et al. (2015), in harvest year 2013 examined the use of a brassica cover crop ahead of spring barley with respect to N dose interaction. This work also demonstrated similar response patterns to the NIAB TAG study with yield responses of c.1.5 t/ha (no additional N) to 0.6 t/ha (150 kg/ha N) recorded in the following crop. Considered collectively these studies provide a five year data set of autumn cover crop use ahead of spring barley. Mean responses for yield and margin over N are presented in Table 64 and show small yield response (c. 0.36 t/ha) and economic benefit (c. £43/ha) in spring barley at N doses typical of a farm standard (excluding the cost of the cover crop seed and establishment). Silgram et al (2015) considered the use of rye and brassica based cover crops ahead of potatoes and while data was variable in this study, conclusions suggested that, subject to seed rate and costs, cover crop use was potentially broadly cost neutral (Stobart et al. 2015; Silgram et al. 2015). However, this research was again relatively short duration and similar to the spring barley examples cited previously it did not look at longer term use or rotational responses.

Table 64 Mean data from studies over five seasons (assumes N at £0.67/kg and barley at £1.20/t)

		No cover crop	Following cover crop
Yield (t/ha)			
0 kg/ha N		3.64	4.60
150 kg/ha N		5.56	5.92
Margin over N (£/ha)			
0 kg/ha N		437	552
150 kg/ha N		567	610

The NIAB led New Farming Systems (NFS) project has considered the longer term yield and margin impacts of cover crop use in UK systems. The research is undertaken at Morley (Norfolk) on a sandy loam soil on large scale fully replicated plots. Research has examined, across a range of combinable crops and rotations, cover crop use (legume and brassica cover crops), approach (including use of autumn sown cover crops ahead of spring sown crops and cover crop bi-cropping systems) and the interaction of cover crop use and primary tillage (comparing inversion and non-inversion tillage systems). Further treatment details are presented in Morris et al. (2014). Yield increases have been detected in a range of crops over the rotation and frequently not just in the crop immediately following the cover crop (Stobart and Morris 2014). Typical margin responses of the order of £50-75/ha (excluding the cost of cover crop seed and establishment) have been recorded in winter wheat within the study from the use of legume and brassica cover crops within conventional arable production scenarios (Stobart and Morris 2011, 2013, 2014). Research examining the interaction of primary cultivation system in the NFS studies is also suggesting different patterns of yield response from the use of cover crops with different cultivation approaches (Stobart et al. 2016). Specifically shallow non-inversion systems have been shown to be more likely to give a positive yield response (Figure 3); (Stobart et al. 2016). It has been proposed that this is associated with improvements to soil structure and the effects of this on (Kruidhof 2008) subsequent crop performance. This suggests that cover crops can potentially lessen the need for cultivations in some situations, and that cover crop use and low disturbance establishment techniques may be well aligned. Recent European work (Abdollahi and Munkholm 2014) has also proposed similar relationships. Field strip comparisons within the Defra SIP project, comparing a range of cover crops to overwinter stubble areas and 'farm standard' autumn non-inversion cultivations (undertaken at the GWCT farm at Loddington on a heavy clay loam soil) have further supported this finding.

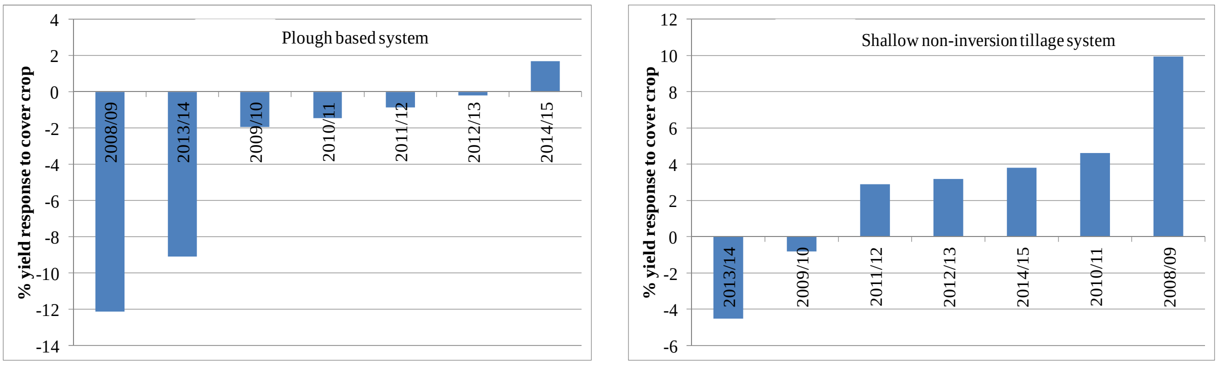

Figure 3 The effect of tillage and brassica cover crop (before spring sown break crops in the rotation) on crop yield (t/ha). Figure a (plough based systems) and b (shallow non-inversion tillage). Crops in specific harvest years were: 2009 (spring oilseed rape), 2011 (spring beans), 2013 (spring barley), 2014 (winter oilseed rape) and 2010, 2012 and 2015 (winter wheat)

5.1.2. Considerations when evaluating cover crops on farm:

The USDA book ‘Managing Cover Crop Profitably’ (Clark 2012) indicates that cover crops provide many benefits, but they’re not do-it-all “wonder crops.” and suggests that to find a suitable cover crop or mix of covers it is important to ‘Clarify your primary needs’; ‘Identify the best time and place for a cover crop in your system’; and ‘Test a few options’.

Given this, when evaluating cover crops, it is important to appreciate that there is no single cover crop system or approach that suits everyone and reasons for use, requirements and fit will differ with circumstance. In addition, depending on objective, repeated use may be required to accrue benefits fully and there is likely to be a learning curve associated with adoption (as would be the case with adopting any new technique). To this end, it is important to think through the approach to be used and set up some ways to assess the impact of the cover crop over time. The following section sets out five key steps to help you do this on farm:

1. Do some research and think about your key objective

Before starting anything in the field think about your key objective and what cover crop approaches you might use to best achieve this (also see section Common cover crop objectives and selection criteria of this review). It can be useful to observe what other farmers in similar circumstances are doing (see the case studies outlined in this review for examples). Identify an information source to inform and guide decisions (i.e. this review). Finally have a plan or schedule; covering areas such as what activity will happen when, what you might expect the cover crop look like at various stages, and what time/equipment/other input or support might be needed over a season.

2. Test a few options (and don't forget about control treatments).

Common approaches to cover crop adoption often initially involve comparing a range of cover crop options that are potentially suited to your goals. An approach to this could be as follows:

- Establish field strips of your chosen cover crops; typically these might be tramline width strips down the length (or part length) of a field.
- Don't forget to include a control strip; in a scenario where a range of cover crop types are being assessed this could be a fallow without a cover crop or a 'farm standard' treatment (such as a typical autumn cultivation). If only one cover crop option is being evaluated a simple field split can be useful.
- Always try to arrange any strips or field splits so that any known variation (e.g. soil type changes or old field boundaries) go across rather than with the splits.
- Ideally replicate these strips within fields and across different fields or sequential seasons, so you can get an idea of variability.

3. Monitor progress and responses

- Monitoring of the comparisons is essential; while this can be as detailed as required, it does not have to be overly complicated.
- Keep records over the season: photographs can be an effective and quick way of doing this, alternatively some simple assessments can be beneficial; for example if your goal was around improving soil structure, periodically over the season dig some holes in the areas with and without a cover crop and assess the structure.
- Quantify the yield response in following crop(s) from both former cover crop and control areas. In many cases combine yield maps can allow this to be done relatively simply. Ensure a yield mapping combine is calibrated and set up with appropriate specific weight values etc. The set up of the yield monitor should not be changed during the harvest of the cover crop areas. If yield mapping is not available, then yield records could also be taken from a combine yield meter, or the yield can be measured using a weigh bridge. Aim to do this consistently across the cover crop areas (e.g. in the middle of an area or at known set points and take a mean). The yield records should be noted in a table or field map against the cover crop/non cover crop areas. The field should be harvested to make comparisons of areas as fair as possible; the header should ideally always be completely 'in work', so that harvested width is constant and ideally combine direction should be the same for all yield measurements within the trial area.
- Research (for example Stobart and Morris, 2014), has shown that not all yield responses associated with cover crop use occur in the crop immediately following the cover crop and some occur in subsequent crops (or even after more than one cycle of cover crop use). Therefore monitor yield one and two years following the cover crop.

4. Evaluate the response.

Any responses to cover crop use should be evaluated. The economic cost and return from the cover crop is an important consideration but this might not be the case where the objective of the cover crop to mitigate against soil erosion or pollution.

- Keep records over the season; this should include seed and input costs as well as estimates of time spent and equipment used. Also do not forget, when comparing this to your control, to include any other relevant management costs that would have been incurred in the control treatment over the period (e.g. time and cultivation costs).
- The economic assessment should be derived from the costs associated with running the cover crop (including seed, establishment, management, destruction etc.) in conjunction with the yield responses over (ideally at least) the following two crops. In some cases additional payments, residual nutrient benefits (e.g. if, for example, phosphate index has been raised this may mitigate the need for other applications and costs) or benefits through environmental schemes (or indirect value perhaps through the management of soil erosion) could also be considered.
- The financial returns cited here do not include any wider benefits (to habitat, soil organic matter (SOM) etc.); and while there is a clear benefit (for example) to improvements in SOM, the financial implications of this are difficult to resolve and are likely to vary with season and circumstance.
- Example costs and returns, based on Stobart (2015), for the value of grain yield margin response (£/ha) for a range of mean grain prices (£/t) at a series of anticipated yield benefits (t/ha) and yield response required (t/ha) for a range of sample cover crop costs (£/ha) at specimen grain prices (£/t) are presented in the Table 75 and Table 86 .

5. Think about next steps

You are unlikely to get everything right in the first use of cover crops, so it is important to consider your evaluation and be prepared to modify and develop the approach and go again. Analogous approaches to that described above could also be used to evaluate other aspects of cover cropping e.g. seeding rates of a cover crop mixture, destruction timing or method or even aspects of in-season management.

Table 75 The value of grain yield margin response (£/ha) for a range of mean grain prices (£/t) at a series of anticipated yield benefits (t/ha)

Grain value per tonne (£)	80	100	120	140	160	180
Yield benefit expected (t/ha)						
0.3	24	30	36	42	48	54
0.4	32	40	48	56	64	72
0.5	40	50	60	70	80	90
0.6	48	60	72	84	96	108
0.7	56	70	84	98	112	126

Table 86 Yield response required (t/ha) for a range of sample cover crop costs (£/ha) at specimen grain process (£/t)

Grain price (£/t)	80	100	120	140	160	180
Sample cover crop cost (£/ha)						
20	0.25	0.20	0.17	0.14	0.13	0.11
40	0.50	0.40	0.33	0.29	0.25	0.22
60	0.75	0.60	0.50	0.43	0.38	0.33
80	1.00	0.80	0.67	0.57	0.50	0.44
100	1.25	1.00	0.83	0.71	0.63	0.56

Other factors to consider:

When growing a cover crop there are a range of practical considerations and steps to adoption. The following 10 point guide lays out a series of factors to consider:

1. Know your objective: think about key objectives and what you want to achieve. Don’t try to chase too many objectives at the same time.
2. Do your homework: observe what other farmers around you or in similar circumstances are doing and identify information sources to inform and guide decisions.
3. Have a plan: very important to think about how you plan to establish and destroy the cover crop and establish the following crop and decide how you will gauge progress (see section on evaluating cover crops on farm). Your plan should also include an estimate of overall budget for the cover crop, likely time commitments and an idea of return or response aspirations.
4. Fit to farm: there is no one answer on whether a cover crop is the right option for you or on what to use. However, whatever you use needs to fit your farm scenario in terms of rotational requirement, fit with soil type and availability of suitable equipment (among other criteria).
5. What to use?: there are a range of options to use as cover crops, some can be expensive and require specific inclusions, but others are cheaper and more readily accessible. Whatever you choose needs to fit the farm scenario and your objective.

6. Mixtures or straights? mixtures are popular and can help spread risk; when choosing a species or mixture (either pre-formulated or your own) it is important to consider practicalities, such as management of variable seed sizes in mixtures, potential rotational conflicts, seed cost and how the components will complement each other. In some situations however, a single species can also be a useful option (e.g. erosion mitigation).
7. Long term commitment: research suggests that not all cover crop responses will be seen in the crop following the cover crop or following the first time of use. Cover cropping is likely to require some long term commitments to start to see the full benefits.
8. Links to environmental schemes: –there are cover cropping options in EFA and Countryside Stewardship schemes that can provide additional returns from cover crop use. These can be worth investigating further
9. Learning curve: accept you are not going to get everything right straight away and that you will be on a learning curve. Try a range of approaches; this is one of the best ways to develop skills and a bespoke system for your own farm.
10. Evaluate, learn and go again: take some time each year to look at what you have done and gauge progress. Based on this be prepared to re-evaluate and modify your approach and to ‘go again’ with a better informed decision based on your findings.

6. Farmer experiences

Seven farmers were asked about their experiences with cover crops on farm, in order to share experiences and inform future work. These farmers represented different types of farm, in different locations and different rotations. These farmers have grown cover crops for a variety of reasons such as improving soil structure, nutrient capture and for forage. Each farmer was asked the following series of questions and the responses have informed the top priorities in section 8):

- Why did you start including cover crops in the rotation?
- What do you hope to achieve by using cover crops
- What are you doing?
- How are you measuring the changes?
- What's worked and what hasn't worked for you?
- What work and research do you think is needed on the subject of cover crops?

The case studies can be found on the AHDB website (https://cereals.ahdb.org.uk/covered)

7. Conclusions

Cover crops are grown primarily for the purpose of 'protecting or improving' between periods of regular crop production. There are four main types of use including; improving soil fertility, improving soil structure, managing weeds and pests and environmental management. Choice of cover crop species or mixture depends on the targeted use of the cover crop. Cover crops are grouped as cereals and non-cereals in the CAP rules, the latter group includes brassicas and legumes.

- Different legume species and cultivars vary in their ability to fix N, ranging from 15 - 325 kg N ha^{-1} yr^{-1}. N fixation is positively correlated with the total biomass of the cover crop.
- N fixation during between late summer and winter was generally between 30 and 100 kg N ha^{-1}, but could be as much as 150 kg N ha^{-1}
- The most active reported soil temperature range for N fixation is between 7°C and 20°C, but the effects of temperature on N fixation varies between species and cultivars
- Mixtures of legumes and non legumes can encourage greater N fixation and lower N leaching risk compared to a straight legume cover crop.
- Uptake of N by cover crops sown in late summer/autumn ranges from 30 to 120 kg N ha^{-1} before spring.
- A C:N ratio of less than 20 is required for net mineralisation (release of plant available N) of crop residues
- Depending on the species and cover crop biomass, destruction method and timing, 10 – 100 kg N ha^{-1} can be expected to be released in the first year of cash cropping following the cover crop. However, in some cases there is a potential negative effect where cover crops such as rye deplete soil N
- Cover crops suppress weeds by physical competition for which early emergence, high seedling vigour, rapid growth and early canopy closure increase competitiveness. However it is often difficult to separate physical competition from allelopathic effects in which chemicals released from cover crops suppress weed growth
- A number of cover crops have been reported to have in-field allelopathic effects which suppress weed growth. Cover crops with allelopathic effects include rye, oats, barley, wheat, triticale, brassicas (oilseed rape, mustard species, radishes), buckwheat, clovers, sorghum, hairy vetch, sunflower, fescues
- The release of allelochemicals from cover crop residues is affected by plant age, vigour and environmental factors and the effectiveness of allelochemicals on weed suppression can be affected by soil texture, organic matter, temperature, light and microbial breakdown
- The effect on cover crops on the total soil organic matter (SOM) content of a soil is variable and difficult to detect because effects take several years to accrue. Some studies have

reported increases in SOM or soil organic carbon (SOC) ranging from 0.3% to 42% relative to treatments without a cover crop, while other studies have reported no change in SOM or SOC. No study reported a decline in SOM. Measures of specific fractions of soil organic matter (e.g. the most recently formed fractions which are more amenable to mineralisation) may be a more sensitive indicator of change.

- The roots of cover crops create biopores in the soil, and can break up compacted soil layers, which can improve subsequent crop root growth.
- If sufficient canopy cover is achieved (30% or more) over winter cover crops have been shown to decrease soil erosion and run off. This was one of the most consistent benefits from cover crops
- Mean yield response of c. 0.36 t/ha from autumn cover crop use ahead of spring barley (five years of data). This gave an economic benefit of £43/ha in spring barley at N doses typical to farm standard (excluding cost of cover crop seed and establishment).
- Typical margin responses of £50 – 75/ha have been recorded in winter wheat within the NFS study lead by NIAB (excluding cost of cover crop seed and establishment) from the use of legume and brassica cover crops.
- The most important agronomic factor for achieving benefits for cover crops is to establish early (late summer/early autumn)
- It is important to set up comparisons of some different options on farm, including a control (farm standard without cover crop), to evaluate the effects in the following crops of the rotation. Testing a few options on farm will allow modifications to be made to ensure that the cover crops are delivering maximum benefit in that specific situation.

8. Current knowledge gaps in the understanding of the function and management of cover crops

This review has identified a number gaps in understanding the function and management of cover crops, which are listed below. Ideally, the effects of cover crops should be assessed in long term, coordinated multi-site experiments. We recommend a network of linked experiments which feature common treatments and basic assessments to enable joint analysis. Satellite projects could be bolted onto this network to answer questions specific to individual farms (e.g. related to soil type or farming system).

Top Priorities:

- There is a need for robust cover crop variety characterisation. Including: disease & pest susceptibility; the impact on other crops in the rotation; the suitability for different environments (e.g. climatic differences and different soil types); suitability in different mixes; rooting capacity; biomass production. This information would be collated in a database and a “recommended list” of cover crops produced. This information could be linked to the Cover Crop and Living Mulch Toolbox developed by the OSCAR European research project (http://web3.wzw.tum.de/oscar/toolbox/database/index.html). Maintaining, updating and developing this toolbox beyond the lifetime of the OSCAR project will be important.
- There is a need to characterise the root systems (rooting depth, architecture etc.) of different cover crops (species/varieties) given the potential period of growth and environments in the UK. The Maxi Cover crop project, funded by AHDB, is investigating this in seven cover crop species and three mixes. This project will characterise the rooting, above ground biomass and nitrogen uptake of the cover crops and study their effects on soil properties and the following spring and winter main crops in the rotation.
- Information on appropriate management of cover crops including; residual herbicide effects, and on diseases, pests and weeds in the main crop. An increased understanding of the impact of management decisions on these factors will form an important part of sustainable crop management and guidelines on cover crop species choice and method/timing of cover crop destruction to maximise pest/disease/weed control benefits from cover crops.
- More data is needed with which to calculate the cost benefits of cover crops. A network of tramline scale trials over several years, carefully designed to ensure that the correct data is calculated to enable gross margins to be calculated and statistically analysed.
- Optimise machinery techniques for the destruction of specific cover crops and the establishment of the following crop for UK conditions and farming systems.
- There is limited UK data on the uptake of soil N during autumn and winter, the effect of destruction timing/methods, soil type and cultivation system on N mineralisation and N availability for following crops, and if the fertiliser N rate for following crops can be reduced.

(This last point could be investigated using N response trials following cover crops). There is also limited data on the cycling of other nutrients (e.g. P, K, S) by cover crops.

- Cover crops grazed with livestock and the effect of this on nutrient availability for following cash crops in UK situations. Management guidelines for cover crop species, establishment dates, livestock species, stocking rate and duration of feeding on the cover crop would help to optimise any benefits of cover crop destruction by grazing.
- There is a need for more long term UK based experiments to measure effects of different cover crops on soil organic matter (SOM) content, which happen slowly over a number of years. Specific SOM fractions may be a more sensitive indicator of change, but guidance on how to use, deploy and interpret these tests is needed.

Medium Priority:

- Identify which legumes are best suited to N fixing in UK conditions (particularly autumn).
- The effect of cover crops on UK relevant weed populations in the following main crops. Effects on both direct competition and allelopathy is required. Allelopathic effects are tested in the field, as glasshouse assays do not always indicate field effectiveness
- Field scale information on the biofumigation effects of different cover crops, and the effect of different destruction timings and methods on soil pests in UK conditions is needed. A current research project is investigating biofumigation as a sustainable replacement to pesticides in potatoes and horticulture crops (project number 114R478)
- Response to starter fertiliser (N and other nutrients) in a range of conditions
- The N_2O release and N leaching contribution from specific cover crop species or mixes grown over winter in UK conditions is not fully understood
- The impact of cover crops (as relatively short term crops) on habitat provision for both beneficial (e.g. natural crop pest enemies), pest species and biodiversity.
- Optimizing crop cover mixes for reduction in erosion and over winter N losses. Extra data on specific cover crop species could be added into the existing FARMSCOPER model
- The effect of cover crops on UK soil mycorrhizal populations and the possible benefits to cash cropping are not fully understood.

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