April 2018

Research Review No. 91

Use of autumn nitrogen in no-till farming systems

Kate Storer[1] John Williams[2] and Pete Berry[1]

[1]ADAS High Mowthorpe, Duggleby, Malton, North Yorkshire. YO17 8BP.

[2]ADAS Boxworth, Battlegate Road, Boxworth, Cambridge. CB23 4NN.

This review was produced as the final report of a 3 month project (211-40028) which started in January 2018. The work was funded by a contract for £15,000 from AHDB Cereals & Oilseeds.

CONTENTS

1. Abstract

Reduced tillage farming systems are increasingly being adopted across the UK, and there is a need to understand their impact on soil nitrogen supply (SNS) for autumn sown crops. The aim of this review is to establish whether autumn applications of manufactured N fertiliser for winter cereals and over-wintering cover crops are required under no-till or shallow min-till conditions. The primary applied N source considered was manufactured N fertiliser. Evidence from peer reviewed publications and relevant industry data was used. The review covers; i) autumn crop N demand, ii) autumn N supply, iii) ability of the crop to acquire N, iv) evidence for the effect of autumn N on crop performance and nitrate leaching, v) conclusions, vi) knowledge gaps and how to fill them.

The difference between autumn crop N demand and the expected N supply (i.e. from the planted seed, atmospheric deposition, soil mineral N (SMN) and mineralisation of soil organic matter and crop residues) under no-till conditions was estimated for winter cereals and winter cover crops. No-till reduced the amount of SMN by 5 to 25 kg N/ha, equalling a 6-29% reduction in the median autumn SNS. There was very little experimental evidence demonstrating the effect of autumn applied manufactured fertiliser N on winter cereal crop performance and nitrate leaching under no-till or shallow min-till conditions, with 15 relevant experiments in total of which only three included a no-till treatment. Under no-till conditions, there was no evidence that autumn applied manufactured fertiliser N increased winter cereal crop yield. One shallow min-till experiment found increased wheat yield following autumn fertiliser N application, but whether the same could have been achieved by altering the spring N application was not tested. Autumn applications of manufactured fertiliser N to cover crops increased crop N uptake, but usually under half of the applied N was taken up. The review concluded that autumn SNS for no-till systems will be sufficient to meet the demand of most winter cereal crops and for winter cover crops to achieve 50% ground cover.

Several factors (soil moisture, quantity and residues, crop type, availability of other nutrients) will also affect crop performance under no-till systems. There was some evidence that autumn applications of manufactured N fertiliser to cover crops increased weed numbers and nitrate leaching. A nitrate leaching model predicted that autumn applications of manufactured fertiliser N (30 kg N/ha) would increase nitrate leaching by 7 to 12 kg N/ha for cover crops or cereal cash crops respectively under low leaching risk scenarios (early crop establishment and low over-winter drainage), whereas all of the applied autumn N could be leached in high leaching risk scenarios.

Overall, the review concludes that 'there is insufficient evidence to change autumn N guidance for no-tilled crops'. However, further research is required to improve the guidance for no-till crops, in particular; the effect of reduced soil disturbance on the availability of all main plant nutrients, how best to manage crop residues in no-till systems, the impact of no-till systems on nitrate leaching losses and spring fertiliser management in no-till systems.

2. Introduction

The 2017 edition of the AHDB Nutrient Management Guide (RB209) for England and Wales recommends that there is no requirement for seed bed nitrogen (N) for winter cereals or cover crops established before winter. For winter oilseed rape with a soil nitrogen supply (SNS) index of 2 or lower, up to 30 kg/ha autumn N can be applied to the seedbed or as a top-dressing to encourage autumn growth but it is suggested that crops sown after early September are unlikely to respond. In Scotland, SRUC Technical Note TN651 (Sinclair & Wale, 2013) advises that autumn N is not generally recommended for winter cereals, as profitable responses are not normally attained and there is an increased risk of N losses to watercourses. However, it is acknowledged that there is a possible N requirement in some winter barley crops that have been direct drilled, established following minimum cultivation, or established after ploughing down large quantities of straw e.g. after carrots.

The guidance given in the AHDB Guide for England & Wales is consistent with Nitrate Vulnerable Zone (NVZ) guidance (2017-20) (www.gov.uk/nitrate-vulnerable-zones). Autumn fertiliser N for cereal crops is effectively ruled out within NVZs due to the closed period for spreading manufactured fertiliser on tillage land starting on 1st September and ending 15th January. An exemption is made for oilseed rape, for which a maximum autumn application of 30 kg N/ha is permitted before 31st October. NVZ rules also state that high readily available N organic manures (with more than 30% of their total N content immediately available to the crop) cannot be applied to tillage land during closed periods (see section 4.3.1 for details).

It is probable that the majority of evidence used to develop guidelines about the use of autumn N were based on ploughed or tilled situations carried our during the last few decades, as per 'conventional' tillage practices at the time. For example, A series of forty eight field trials conducted in the UK in the 1980s found that autumn N was not economically beneficial, and that, although a few sites had a positive yield response to autumn N application, it was not predictable and it generally did not exceed that obtained from equivalent quantities of spring N (Sylvester-Bradley *et al*., 1996). Vaidyanathan & Turley (1992) found no unique yield benefit from 40 kg N/ha when applied in the autumn where straw was chopped and shallow-incorporated that could not be achieved with adequate N applied in the spring. An AHDB review of a large number of experiments (Prew *et al*., 1988) found that 40 kg N/ha applied in autumn was on average uneconomic regardless of method of straw disposal, when compared to applying the N in spring. More recently, a series of six experiments on winter barley established following ploughing demonstrated no significant benefit of autumn N application above those seen when the nitrogen was applied in the spring (Kendall *et al*., 2017).

No-till and minimum tillage farming systems are increasingly being adopted across the UK to reduce input costs and as a consequence of increasing concern in potential negative effects of ploughing (Soane *et al*., 2012). For example, in 2015, minimum tillage methods were the dominant cultivation methods in Yorkshire and Humber with an estimated 70% of wheat land after oilseed rape and pulse crops established using this method, although <1% of these crops were direct drilled in this region. Similarly in the south of the UK an estimated 45% of crops were ploughed, 50% min-tilled and 5% direct drilled (ADAS, 2015). Cover crops are commonly established by drilling directly into crop residues of the previous crop.

It is well understood that under no-till cultivations the level of N mineralisation is lower (Dowdell *et al*., 1983), and immobilisation of N due to incorporation of previous crop residues is higher compared with using conventional ploughing (Van Den Bossche *et al*., 2009). A review of literature (Silgram & Shepherd, 1999) showed that ploughing and deep soil cultivations result in more N mineralisation during autumn than direct drilling or minimal cultivations. It could therefore be argued that the requirement of autumn applied N may be greater for crops established using no-till and minimum tillage approaches compared with ploughing and deep tillage. In order to understand the potential benefit of autumn N in these situations it is important to recognise that many other factors influence autumn SNS and the crops ability to take up N in the autumn including; sowing date, previous crop, the quantity and type of residues left over from the previous crop, soil type, and soil structural conditions.

It is clear that the impact of cultivation depth and intensity is a key factor in determining the amount of plant available N by affecting the processes of N mineralisation and N immobilisation. There are many types of cultivation method which are defined in Table 1. Throughout the review, these definitions will be used to distinguish between the main cultivation methods used within the reviewed experiments. The review also recognises that there is a wide range of cultivation and drilling equipment available, all of which will create different seedbed conditions and therefore may not be directly comparable even if they disturb the soil to the same depth.

It is also important to recognise that limited N supply may not be the only cause of poor autumn crop growth under no-till systems. Other factors that will restrict crop growth in the autumn include poor soil structure (which will reduce drainage and cause waterlogging and lack of oxygen), poor root development and reductions in the availability of other nutrients (e.g. P and S). Lundy *et al*. (2015) summarised a range of papers outlining potential causes for reduced yields under no-till conditions, which included delayed or uneven germination, lower soil temperatures, waterlogging, weed competition, increased disease risk, as well as potential N-immobilisation from residues. Given the current restrictions on N fertiliser use in the autumn in the UK under NVZ rules and the potential environmental risks from nitrate leaching or nitrous oxide (N_2O) emissions, it will be important to understand whether autumn N application provides any additional benefits above applying the additional N in the spring alone.

Cover crops represent a unique crop type, with their main aim usually considered to 'protect or improve' between periods of cash crop production (White *et al*., 2016). Consequently, cover crops will require different approaches for evaluating the potential benefits of autumn applied N compared with cereal cash crops. Cover crops are most frequently sown following early harvested combinable crops in the summer (ca. August), and will be left in the ground until the following spring (ca. February) when they are often incorporated into the soil ahead of a planting a spring cash crop. On lighter land, it is also possible to establish cover crops following late harvested crops (e.g. maize) (White *et al*., 2016). Generally, greater benefits are seen from the earlier sown cover crops, as they enable greater biomass to develop and provide better soil protection (Balkcom *et al*., 2012). Cover crops are generally grown for one of four main purposes including; improvement of soil fertility, improvement of soil structure, managing weeds and pests and environmental management (including reducing nitrate leaching) (White *et al*., 2016). Therefore the effect of autumn N application on each of these potential roles will need to be considered. For instance, any application of autumn N will need to increase the uptake of soil mineral N (SMN) above that which would be achieved without the autumn N application, as well as taking up the applied autumn N, in order to avoid the risk of greater leaching losses. This might be through improving plant establishment or resilience against pest damage. However, any application would also need supporting evidence of economic value, which would require clear yield responses in the following spring cash crop to justify application. Evidence will also be required to demonstrate that there would not be a greater risk of environmental losses (e.g. nitrate leaching or N_2O emissions) following cover crop destruction in the following spring.

The aim of this review is to evaluate available evidence about the use and efficacy of autumn applications of manufactured N fertiliser for winter cereals and over-wintering cover crops under no-till conditions. The review focusses on no-till conditions, but makes use of information from shallow min-till conditions (<10 cm deep) where relevant. The primary N source considered was manufactured N fertiliser, but evidence relating to organic materials with high levels (>30%) of plant available N were also considered where appropriate. Evidence from peer reviewed publications and relevant industry data has been collated.

The review addresses the following topic areas;

i) crop requirement for autumn N
ii) supply of N from seed, atmospheric deposition and mineralisation, together with potential losses to the environment
iii) ability of the crop to acquire N in the autumn

iv) experimental evidence for the effect of autumn N on crop yield, crop quality, plant establishment, ability to tolerate biotic and abiotic stresses, pollution (e.g. nitrate leaching, N_2O production), and cost effectiveness
v) conclusions about whether autumn N is required
vi) knowledge gaps and recommendations for how to fill them.

Table 1. Definitions of the main cultivation methods used in the UK. Terminology which shares a definition is indicated by tick marks.

		Alternative/shared terminology							
Name	**Definition**	**No-till or Zero-till**	**Min-tillage**	**Inversion tillage**	**Non-inversion tillage**	**Conserv-ation tillage**	**Reduced tillage**	**Eco-tillage**	**Lo-Till**
Direct drilling	No cultivation prior to drilling, or very minor soil disturbance	✓			✓	✓	✓		
Shallow tillage	< 10 cm without inversion		✓		✓	✓	✓	✓	✓
Deep tillage	> 10 cm without inversion				✓	✓	✓		
Strip-tillage	Strips are tilled and sown with residue moved onto the untilled strips.		✓*		✓	✓	✓		
Conventional Ploughing	Inversion tillage			✓					

Davies, 1988; Davies & Finney, 2002; Stobart & Morris, 2011; Townsend *et al*., 2016

3. Principles of crop nitrogen requirement in the autumn

3.1. Crop nitrogen demand

3.1.1. Winter cereals

There are a number of ways in which autumn applied N may be considered beneficial for a winter cereal crop, for example if it were to improve plant establishment and plant vigour so that the crop could tolerate pest damage, improving rooting and therefore subsequent nutrient uptake or, through causing unique yield or crop quality increases that could not be achieved with changes in spring N management. Benchmark values of high yielding winter wheat and winter barley crops are available for the growth and N uptake in February from the datasets used to produce the Wheat and Barley Growth Guides (AHDB, 2015a; AHDB, 2015b; Blake *et al*., 2006; Spink *et al*., 2000) . These datasets included nine winter wheat crops growth at three sites in England over three seasons and 18 winter barley crops grown at six sites over three seasons. For crops sown in September or October, most crop growth up to February occurs in the autumn. Therefore, these benchmarks of growth and crop N uptake can be considered as approximate targets for crop N requirement during the period between drilling and winter.

The benchmarks for N content in the above-ground parts of the crop in February during tillering were 22 kg N/ha for winter wheat and 24 kg N/ha for winter barley. By GS30, cereal crops have produced about 0.5 t/ha of root biomass (AHDB, 2015a). If the N concentration in roots is assumed to be 1% (Porter, 1993), then the root biomass will contain about 5 kg N/ha. This will therefore give a total N demand of 27 and 29 kg N/ha for wheat and barley respectively by February. While the total N requirements are likely to be greater for a higher yielding crop, or milling wheat, this is unlikely to make a difference to the autumn N requirement, e.g. it has been shown that early N limitation in winter wheat is unlikely to have a detrimental effect on grain protein content (Ravier *et al*., 2017). While this approach enables the total crop N requirement during autumn to be estimated, it should be recognised that it doesn't account for temporal effects of N availability to the crop as affected by the timing of mineralisation. This may also be important, particularly for improving plant establishment or to tolerate pests such as slugs.

Table 2. Estimated demand for autumn N uptake by high yielding winter wheat and winter barley crops (kg N/ha).

	Winter wheat	Winter barley
Benchmark N uptake into the crop foliage by February	22	24
Estimated N content of the roots	5	5
Canopy N requirement by February	27	29

3.1.2. Cover crops

Cover crops can generally be split into three main groups, brassicas (e.g. mustards, radishes, turnips), legumes (e.g. vetch, clovers) or grasses and cereals (e.g. oat, rye, rye-grass) (White *et al*., 2016), although there are a few species that do not fit into these categories (e.g. buckwheat, chicory and phacelia) (White *et al*., 2016). Benchmark values for cover crop N uptake are not known. Table 3 summarises both the 'typical' autumn/winter N requirement values from the literature, along with estimated 'potential' autumn/winter N requirement values for target ground covers and canopy sizes. The GAI required to cover 50% or 75% of the ground has been estimated using the Beer's law equation $F = e^{(-kL)}$ where F is the fraction of ground not covered by crop (when viewed from directly above), L is the green area index and k is the extinction coefficient assumed to be 0.5 for cereals and pulses and 0.75 for brassicas (Berry *et al*., 2011a). The estimated values are based on the crop N requirement values for similar cash crops, which are 32 kg N/ha/GAI unit for cereals (mean of benchmark values for winter wheat and barley reported in Table 2), 50 kg N/ha/GAI unit for brassicas (Berry *et al*., 2011a), and legumes are assumed to be the same as cereals at 30 kg N/ha/GAI unit. In summary, cover crops would need to take up approximately 50 kg N/ha to achieve 50% ground cover and approximately 100 kg N/ha to achieve 75% ground cover. It should also be recognised that if the main purpose of the cover crop is to reduce the risk of soil erosion then a smaller crop cover of over 30% has been shown to reduce the erosion risk (White *et al*., 2016). Using the same principles as described above the GAI required to achieve 30% ground cover would be approximately 0.5 for brassica crops and 0.75 for cereal/legume crops. Crops would need to take up approximately 30 kg N/ha to achieve these canopy sizes.

An understanding of typical crop N uptake values over winter will help to understand the N requirement under current management methods, whether there is potential for this to be increased, and under what circumstances this may or may not be beneficial. White *et al*. (2016) reviewed the literature for typical autumn/winter N uptake values of hairy vetch (*Vicia villosa*), rye (*Secale cereal*), crimson clover (*Trifolum incarnatum*), white senf mustard (*Brassica hirta*) and oilseed radish (*Raphanus sativus*). The N uptake values ranged from 28 up to 154 kg N/ha, demonstrating the importance of understanding the difference between cover crop species and the potential they have for taking up N in the autumn. These ranges could be broadly grouped into brassicas, legumes and cereals and the averages are summarised in Table 3. Data given in the literature is usually only for the above ground biomass and N uptake. It is therefore necessary to estimate how much N will be required for root growth. This is estimated at 5 kg/ha using the same assumptions as for the cash crop cereals described in Section 3.1.1. ADAS unpublished data from 2 experiments shows that root biomass of oilseed rape at the 6 leaf stage varied between 9 and 13 g per plant, with an average biomass of 10 g per plant. The average plant population was 70 plants/m^2 which gives a root biomass of 0.7 t/ha. If the N concentration in this tissue is assumed to be the same as cereals at 1% then the amount of N in the roots in autumn would amount to about 7 kg/ha.

It is recognised that cover crops are often grown as mixtures of species from across the cover crop categories. However, insufficient information was available to specify typical N uptake for the very wide range of species mixtures which can be used.

Table 3. Typical estimated cover crop N demand (kg N/ha) over autumn/winter calculated based on either typical GAI and N uptake values or from measured averages reported in the literature.

	Brassicas	Legumes	Cereals
Typical above-ground autumn/winter N uptake[a]	93 (57-127)	91 (28-154)	46 (30-61)
Typical above & below-ground autumn/winter N uptake[b]	100 (64-134)	96 (33-159)	51 (35-66)
GAI required to reach 50% ground cover[c]	1.0	1.5	1.5
Above-ground N uptake required for 50% ground cover[c]	50	45	48
Above and below-ground N uptake required for 50% ground cover[c]	57	50	53
GAI required to reach 75% ground cover[c]	2	3	3
Above-ground N uptake required for 75% ground cover[c]	100	90	96
Above and below-ground N uptake required for 75% ground cover[c]	107	95	101

[a]Mean (range) of values for all reported brassicas, legumes or cereals in White *et al*. (2016).
[b]Mean (range) of values for all reported brassicas, legumes or cereals in plus the estimated N content in the roots of brassicas or cereals as calculated in the main text.
[c]Calculated using Beers law and benchmark canopy N requirement values for equivalent cash crops as described in the main text.

3.2. Soil supply of nitrogen in the autumn

The autumn SNS is determined by the relative rates of mineralisation, immobilisation and loss of N from the system via nitrate leaching to water and gaseous losses (e.g. N_2 and N_2O) to the atmosphere. Atmospheric deposition of N also adds to the SNS. The total supply of plant available N is the net result of these input and loss processes, as shown in Figure 1. These processes can be affected by a wide range of factors including cultivation method, soil temperature, soil water content, soil texture, soil organic matter content, previous crop, whether previous crop residues are incorporated or not and the crop residue C:N ratio. The following sections will estimate the relative values of these processes and review the evidence for the effects of no-till or min-till cultivation methods.

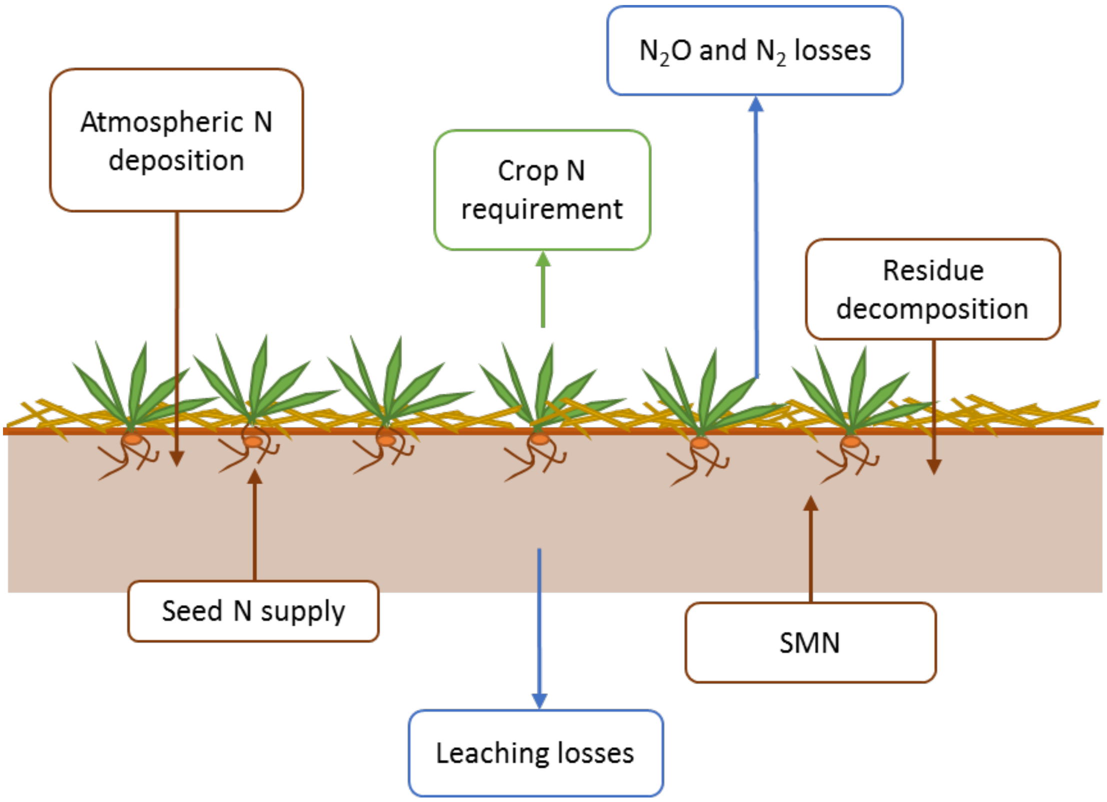

Figure 1. Main sources and sinks of nitrogen (N) available to an autumn sown crop following direct drilling with approximate values. The crop will have access to N from the seed N supply, atmospheric deposition of N, previous crop residues and the SMN, the net availability of N will depend on losses of N via leaching and gaseous N losses. Brown boxes represent N inputs, blue represent N losses and green represents the crop N demand.

3.2.1. Seed N supply

The provision of N from the seed store is very important as it provides a source of N for early growth that is unaffected by the N status of the soil. Winter wheat seed has a typical N concentration of 2% on a dry basis, and a typical grain weight of 42 mg on a dry weight basis, suggesting that there is approx. 0.85 mg N per seed. At a seed rate of approx. 300 seeds/m^2, this would equate to approx. 3 kg N/ha. The wheat growth guide reports that approx. 5 kg/ha of N comes from the seeds (AHDB, 2015b). Winter barley in contrast has a typical N concentration of 1.76% for feed barley, with a typical grain weight of 39 g on a dry weight basis, suggesting there is approx. 0.69 g N per seed for feed barley varieties. At a seed rate of approx. 300 seeds/m^2, this would equate to approx. 2 kg N/ha for feed varieties. Examples of seed N contents for wheat and barley at a range of seed rates can be found in Table 4. In winter wheat, one GAI requires 36 kg N/ha, so 5 kg N/ha provided by the seed will enable a crop to produce a GAI of up to 0.14. In barley, at 300 seeds/m^2, 2.1 kg N/ha would equate to an approx. GAI 0.08 for feed varieties, based on barley requiring 28 kg N/ha to create one GAI unit.

There is less information available on the seed N contents of cover crop species, which have been grouped into cereal, brassicas and legumes in Table 5. These values are based on estimates from cereal (winter wheat and winter barley), brassica (winter oilseed rape) and legume (winter beans) cash crops and therefore may be at the upper end of the range as these seed N% values are likely to have come from crops which have received high levels of N fertiliser. The potential GAI produced from the seed N stores is also included in Table 5 and is also based on similar cash crop estimates for canopy nitrogen requirement.

Table 4. Typical seed N contents for a range of seed rates of winter wheat and winter barley.

Seed rate (seeds/m^2)	Winter wheat (kg N/ha)	Winter barley (kg N/ha)
200	1.7	1.4
300	2.7	2.1
400	3.4	2.8
500	4.3	3.5

Table 5. Seed N content details for cereal, brassica and legume cover crops based on cash crop values for typical seed N% and seed rates and potential GAI produced from the seed N supply.

Cover crop	Seed N%	Seed rate[†] (kg/ha)	Seed N content (kg N/ha)	Potential GAI
Cereals[a]	2	30 - 100	0.6 - 2	0.02 - 0.06
Brassicas[b]	3[b]	4 - 15	0.12 - 0.45	0.002 - 0.23
Legumes[c]	4[d]	100-200	4 – 8	0.08 – 0.16

[†]Estimated seed rates based on typical values reported by White *et al*. (2016).

[a]Assuming canopy N requirement of 32 kg N/ha/GAI for winter cereals (mean of wheat and barley values).

[b]Assuming canopy N requirement of 50 kg N/ha/GAI for winter oilseed rape (Berry *et al*., 2011b) and seed N% of 3% for winter oilseed rape (Berry *et al*., 2010).

[c]Seed rates based on winter beans

[d]Assuming protein content of ca. 25% (estimate based on winter bean (PGRO, 2016)) and conversion to N of 6.25.

3.2.2. N-fixation by legumes

Legumes are often included in cover crop mixes as they can fix atmospheric N and provide an additional source of N. White *et al*. (2016) reviewed the levels of N-fixation by cover crops at different times of year, concluding that between late-summer and winter, a leguminous cover crop under UK conditions may fix between 30-100 kg N/ha. This may not all be retained by the crop, and will be affected by the sowing date of the crop, as N-fixation is most likely at temperatures ranging from 7-20^{o}C. There is also typically a delay between germination and the initiation of N fixation as the nodules need time to form (Cuttle *et al*., 2003; White *et al*., 2016). Nonetheless, this represents a substantial source of N for legumes. The earlier the legume is sown, the more likely it is to form nodules and fix N before winter.

3.2.3. Atmospheric deposition

In recent years, air pollution by N substances has been decreasing (DEFRA, 2018), and the average rate of N deposition to moorland and short plant areas in the UK between 2012- 2014 was 16 kg N/ha per year (CEH, 2018; DEFRA, 2012). Approximately 50% or 8 kg/ha of deposited N is thought to become available to a winter wheat crop and about one third of it is deposited over the winter months (Goulding *et al*., 1998), thus approximately 3 kg/ha N can be assumed to be available to winter cereal crops over the autumn/winter period.

3.2.4. Mineralisation and immobilisation of nitrogen

Mineralisation is the process by which N bound in organic materials becomes available for plant uptake. Immobilisation is the reverse of mineralisation. This section will review the evidence for impacts of direct drilling on the balance between mineralisation and immobilisation of nitrogen. Wade *et al*. (2006) found no difference in SMN between ploughed and reduced tillage (down to 20 cm) treatments. Average SMN levels were 77 kg/ha in the reduced tillage treatment, compared to 73 kg/ha in the ploughed treatment. Site (soil type) and season (drier vs wetter) appeared to have the greatest effect on SMN levels across 9 site/year studies. Similarly, there was no significant difference between cultivation treatments on spring SMN. The reduced tillage treatments in 8 of the 9 sites were to 15 – 20 cm depth, which is recognised as being quite deep, but one site was direct drilled and still showed no significant difference in SMN compared with the ploughed treatment.

In contrast, on a shallow (<30 cm) calcareous fine loam over chalk soil, bi-weekly early season cultivation using a straight tine from harvest until drilling resulted in a greater level of nitrate (22 µg/g dry soil) compared to the non-cultivated plots (14 µg/g dry soil). Both treatments were then ploughed at drilling in early September, and the trend remained until November. Thus, even delaying the date of soil disturbance in this case resulted in lower levels of nitrate in the soil (Stokes *et al*., 1992).

In a series of UK experiments on autumn sown crops (mainly winter cereals), the apparent net mineralisation of organic N (balance of crop N, SMN and leaching) in autumn and winter was not significantly different between direct drilled (26 kg N/ha) and ploughed (31 kg N/ha) plots. Yet, over the year the rate of mineralisation in the ploughed plots (83 kg N/ha) when compared to the direct drilled plots (67 kg N/ha) was 16 kg N/ha higher (Goss *et al*., 1993).

Across two winter wheat experiments on light-medium textured soil sites in Switzerland, the SMN measured to 90 cm depth at the end of winter was highest under minimum tillage (15 cm depth), followed by the no-till treatment and lastly the conventional tillage treatment (25 cm depth), however only the min-till and conventional tillage treatments were significantly different (Rieger *et al*., 2008). There was also a significantly lower plant number in the no-till treatment compared to the conventional tillage, with the min-till treatment plant population being between the two. This trend followed through to tillering, where the shoot biomass was lower under no-till compared to the conventional tillage treatment, but the crops produced compensatory growth and these differences declined by flowering. Consequently, by harvest there was no significant difference in shoot biomass between the cultivation treatments, although there was a trend ($P<0.1$) for lower yield under the no-till system compared to the min-till and conventional treatments due to significantly lower thousand grain weight. The levels of *Fusarium* infection were higher in the no-till treatments, which is likely to be driven by the higher level of the pathogen remaining in the crop residues from the previous crop. Interestingly, there was no significant difference in the wheat crop's response to spring N fertilisation (zero N fertiliser vs. recommended fertiliser N) between the cultivation treatments. Thus, the authors suggest that differences in N supply was not a limiting factor in the production of winter wheat under any of the three cultivation treatments (Rieger *et al*., 2008).

A review of the effects of cultivation on soil N mineralisation by Silgram and Shepherd (1999) concluded that there could be large differences in the SNS following no-till and mouldboard ploughing, with between 5 - 65 kg/ha higher SMN levels recorded from ploughing than from no-till conditions. The ploughed sites also had a greater risk of nitrate leaching of up to 25 kg N/ha (20-50% increases). In general, if moisture wasn't limiting, the authors suggested that no-till sites resulted in slightly lower yields, and may have a small additional N requirement of up to 25 kg N/ha to alleviate this difference. This was because the levels of annual net N mineralisation may be 5-25 kg/ha lower under no-till conditions, partly due to increased N immobilisation from high C:N ratio crop residues near the soil surface. The authors concluded that under the right soil type and conditions (avoiding sandy soils), no-till could be a useful method for reducing nitrate leaching, but that it may also require up to 25 kg/ha additional fertiliser N to boost yields up to those seen in conventionally ploughed crops. The effect of ploughing on mineralisation following several years of min-till was raised as an area of uncertainty, in which there may be a greater release of SMN (Silgram & Shepherd, 1999). Subsequently, in a study in the Brimstone Farm Experiment, Oxford, UK, it appeared that more nitrate was leached from land that had been under minimal or zero tillage for 8 years and then ploughed compared to land which had been ploughed each year, thus considering a single season is often not sufficient to consider longer term environmental impacts (Catt *et al*., 2000).

Under UK conditions, median soil N supply (SNS) (crop N content plus SMN to 90 cm depth) values in late November/early December reported from 164 sites were 87 kg N/ha, with a range from 16 to 776 kg N/ha (Kindred *et al*., 2012). These sites were predominantly ploughed sites, with some min-till sites included, and a range of residue inputs (Kindred *et al*., 2012). The median SNS was 40 kg N/ha for the 0-30cm soil horizon and 70 kg N/ha for the 0-60 cm soil horizon. The bottom 10% of values had an SNS of less than 34 kg N/ha in the 0-60 cm horizon and less than 46 kg N/ha in the 0-90cm horizon. The bottom 20% of values had an SNS of less than 43 kg N/ha in the 0-60 cm horizon and less than 57 kg N/ha in the 0-90cm horizon. The median 0-30 cm SNS from Kindred *et al*. (2012) is in agreement with Shah *et al*. (2017) who reported median 0-30 cm SMN values across 8 UK sites in early September of 43 kg N/ha (just prior to or shortly after drilling of cover crops). Silgram and Shepherd (1999) reported that N mineralisation levels may be 5 – 25 kg N/ha lower under no-till across the whole season, therefore SNS could be considered to be up to 25 kg N/ha lower under no-till conditions. Under no-till conditions this would equate to an SNS to 90 cm soil depth of approximately 62-82 kg N/ha and 45-65 kg N/ha to 60 cm soil depth, if the reduced effect of mineralisation was entirely in the top 60 cm (which is reasonable given that surface residues may be the cause). The bottom 10% of fields may have SNS values of less than 9-29 kg N/ha in the 0-60 cm horizon. The bottom 20% of fields may have SNS values of less than 18-38 kg N/ha in the 0-60cm horizon.

Residue N contents

There are physical, chemical and biological challenges associated with residues from previous crops and no-till methods. The physical challenges in relation to chopping and spreading the straw are reviewed by Morris *et al*. (2010), as are the potential allelopathic effects of residues on seed germination. Generally straw residues are recommended to be spread such that the crop residues and planted seed are not closely located, and in most cases the straw is chopped and spread very evenly (Soane *et al*., 2012). Once established, the residue C:N ratio will also be important in determining the conditions for crop development over winter (Mary *et al*., 1996).

A C:N ratio of 30:1 or above is generally thought to be the point at which net immobilization occurs, and net mineralisation thought to occur at C:N ratios of approx. 25:1, with increasing N available to plants as the C:N ratio decreases (Hodge *et al*., 2000). The N content of previous crop residues will also contribute directly to the autumn SNS if straw is mineralised quickly. Measured C:N ratio of crop residues and N return in crop residue to the following crop are summarised in Table 6. Cereal straw can contain approx. 0.6% N, whereas oilseed rape can contain up to 1% N (Nicholson *et al*., 2014), but the large returns of residues can mean that there are quite large N returns to the following crop. However, it should be recognised that for high C:N residues the majority of this N return will usually occur in the spring and summer. The risk of N lock-up via immobilisation of N has been discussed in a review on straw incorporation, and 1 t cereal straw can immobilise ca. 10 kg N/ha. The demand for this N was within 2-3 months of straw incorporation (Nicholson *et al*., 2014). However, this review focused on incorporating straw, for no-till crops, the straw would remain on the soil surface.

Table 6. Range of C:N ratios of residues from previous crops and N return over the whole following growing season.

Crop	Residue type	C:N Range	N return in residues (kg N/ha)	References
Sugar beet	Tops	12-25	82-211	Jarvis *et al*., 1996; Sylvester-Bradley *et al*., 2015
Vining pea	Haulm inc. pod walls	14-30	138-349	Sylvester-Bradley *et al*., 2015
Combining pea	Straw & pod walls	28-37	10-404	Sylvester-Bradley *et al*., 2015
Potatoes	Haulm	16-30	41	Jarvis *et al*., 1996
Dried peas	Haulm	20-63	48	Jarvis *et al*., 1996
Winter & spring field beans	Haulm	33-58	22-206	Jarvis *et al*., 1996; Sylvester-Bradley *et al*., 2015
Oilseed rape	Haulm	22-96	65-108	Jarvis *et al*., 1996; Sylvester-Bradley *et al*., 2015
Winter wheat	Straw	50-122	26-66	Bhogal *et al*., 1997; Sylvester-Bradley *et al*., 2015

Residue C:N ratio is important in determining the rate of mineralisation and whether net mineralisation tips to immobilisation. However, a study by Van Den Bossche *et al*. (2009) on silty loam sites in Belgium found that under no-till (direct drilled), more N was immobilised than under conventional tillage (mouldboard plough, to a depth of 25-30 cm), with a similar trend for increased immobilisation in the reduced tillage (non-inversion, using a cultivator or soil loosener) treatment. Indicating that the degree of soil disturbance is also important in determining the relative balance between mineralisation and immobilisation. The authors therefore concluded that there is less risk of nitrate leaching under reduced tillage. However, the paper did not report the impact of contrasting residues on the yields and quality of the following cash crop.

In contrast, a study in Northern France found that tillage method (mouldboard ploughing to 30 cm vs minimum tillage to a depth of 5-8 cm) had no effect on the level of ^{15}N immobilisation, but there were higher CO_2 levels measured following ploughing when compared to minimum-tillage, suggesting that this treatment had higher levels of microbial activity. The authors proposed that this may have been a result of the crop residue depth in the soil, since it was incorporated to a lower depth the soil-residue contact may have been increased, which could have consequently increased decomposition rates in the ploughed plots (Giacomini *et al*., 2010).

This is in agreement with previous studies as reviewed by Kumar & Goh (1999) and Schoenau & Campbell (1996). Under no-till, residues will be left on the soil surface which can result in slower rates of decomposition as the conditions (temperature, moisture and availability of mineral N) are not conducive to microbial growth and therefore decomposition, particularly for residues with a high C:N ratio (Kumar & Goh, 1999; Schoenau & Campbell, 1996; Schomberg *et al*., 1994). In contrast, for crops with a lower C:N ratio, the risk of volatilisation of ammonia (NH_3) may be increased (Schoenau & Campbell, 1996). Consequently, Schoenau and Campbell (1996) suggested that placement of N fertiliser would help to reduce the risk of volatilisation and immobilisation of N due to residues.

3.2.5. Nitrate leaching and gaseous losses of N

A long-term study in Denmark on two field experiments each including four cash crop rotations found that across all sites and years direct drilling and cultivating to two different depths did not affect the rate of nitrate leaching (Hansen *et al*., 2015), although yields were reduced in the direct drilled crops. Straw retention also did not reduce N leaching or improve yields (Hansen *et al*., 2015). Similarly, in a series of field scale trials in the River Wensum Demonstration Test Catchment Project, Norfolk, UK, Cooper *et al*. (2017) found that direct drilling and shallow inversion tillage did not reduce soil water nitrate N and P concentrations when compared with ploughing. In a review on no-till use in northern, western and south-western Europe, Soane *et al*. (2012) concluded that there was a lack of consensus in the literature on whether no-till impacted upon nitrate leaching. Nitrate leaching losses depend on several factors including crop type, sowing date, soil type, soil structure and the amount of excess winter rainfall (drainage) (Soane *et al*., 2012). Goss *et al*. (1993) reported an increase of 21% in total nitrate leaching from drained plots which had been conventionally ploughed to 20 cm depth, compared to direct drilled plots with < 5cm depth disturbance (from incorporation of ash residues following straw burning on some sites). However, there could sometimes be increased nitrate leaching from the direct drilled plots in the spring, potentially as a result of the higher levels of nitrate left in the soil over winter. There was also higher denitrification reported in the direct drilled plots, representing another potential N loss pathway.

N_2O emissions under no till were reviewed by Soane *et al*. (2012) who concluded that N_2O emissions from tilled vs no-tilled treatments were often highly variable, with changes in the N_2O emissions from no-till treatments across four studies ranging from 48% up to 324% of the ploughed treatment. There often appears to be greater N_2O emissions from poorly-aerated soils under no-till vs ploughed conditions, and little impact of cultivation on N_2O emissions when the soils are well aerated (Rochette, 2008). Duration under no-till may also be important (Six *et al*., 2004), as may timing and frequency of the N_2O measurements (Regina & Alakukku, 2010). Under very wet conditions, denitrification will result in conversion of N_2O to N_2 which can be a significant source of gaseous N loss (Davidson, 1991). Since no-till practices may increase moisture content and reduce aeration (Martens, 2001; Soane *et al*., 2012), there is a risk that this may also result in higher losses of N_2.

3.2.6. Autumn soil N supply summary

The autumn supply of N available to the crop is the net result of the processes outlined above, namely seed N supply, atmospheric deposition, net mineralisation as affected by cultivation and previous crop residue type and quantity, and nitrate leaching and gaseous N (Figure 1). The seed N supply and atmospheric deposition will be the same, regardless of cultivation method. However, it is clear that the net mineralisation, leaching and gaseous losses can be affected by cultivation, and thus may have an impact on the soil N supply to the crop. Whilst the effect of no-till on mineralisation has been reported as reducing rates by 5 – 25 kg/ha, the effect of no-till on leaching and gaseous losses is more difficult to quantify, and therefore can't be estimated with any certainty here.

In order to estimate the potential crop fertiliser N requirement in autumn, we have calculated the difference between the estimated autumn crop N demand and estimated autumn soil N supply for both winter cereals (Table 7) and cover crops (Table 8). Crops need a root length density of 1 cm of root per cubic cm of soil to extract all available water and nitrate from the soil (King *et al*., 2003) and crops quickly exceed this density in the soil surface (King *et al*., 2003). Wheat roots can grow at a rate of 12 mm per day during autumn (AHDB, 2015b). Therefore, cash crops established in early autumn would be expected to reach at least 60 cm depth by winter. If the same rate of root growth of 12 mm per day is assumed for cover crops, cover crops sown in August may be expected to reach depths of over 90 cm by winter. Therefore the autumn SNS most applicable for cash crops will be the SNS to a depth of 60 cm (45 to 65 kg N/ha). For early sown cover crops, the most applicable SNS is likely to be to a depth of 90 cm (62 to 82 kg N/ha).

Winter cereals

The estimated excess autumn SNS for winter wheat and winter barley is summarised in Table 7. Given the similar canopy N requirement up to GS30, there is very little difference in the excess SNS, which is approximately 20-40 kg N/ha to a depth of 60 cm, and 35-55 kg N/ha to 90 cm depth. The reported SNS are median values for UK crops (described in Section 3.2.4), thus for the majority of UK winter cereals, and applications of manufactured fertiliser N would not be required to reach a high yielding benchmark N content by GS30.

Table 7. Estimated demand for autumn N uptake by high yielding winter wheat and winter barley crops (Table 2) and autumn soil N supply (SNS) (kg N/ha) at two depths with calculated N balance.

	Winter wheat	Winter barley
Crop N requirement by February	27	29
Autumn SNS (0-60 cm)	45-65*	
Autumn SNS (0-90 cm)	62-82	
Balance of autumn SNS (0-60 cm) minus crop N requirement	18-38	16-36

*Assuming reduced mineralisation is located in the top 60 cm of soil.

Winter cover crops

The cover crops which may have a demand in excess of the autumn SNS are indicated in bold and underlined in Table 8. Where typical values are used to estimate crop N demand, the brassicas and legumes may have a requirement for additional fertiliser N, above that provided by the autumn SNS. However, the legumes ability to fix N has not been accounted for here, and may equate to between 30-100 kg N/ha over late summer and winter, depending on how early the crop was sown (reviewed by White *et al*. (2016)), legumes are therefore likely to fulfil their own N requirement via N-fixation in systems where the SNS is insufficient. The autumn SNS under no-till conditions is estimated to exceed the typical cereal N demand. It is estimated that the autumn SNS should be sufficient to meet cover crop N demand if the target for cover crop growth is a ground cover of up to 50%. However, if the target ground cover is 75% then the autumn SNS is estimated to be insufficient for all three cover crop types. This analysis indicates that the autumn SNS under no-till will only be insufficient to meet the N demand of cover crops when the target ground cover is high (75%). It should be recognised that substantially lower ground covers of 30% are often sufficient to achieve cover crop function, e.g. reducing the risk of soil erosion. A ground cover of 50% will be sufficient to take up at least 50 kg N/ha which will reduce the risk of nitrate leaching.

It is important to recognise that cover crops are often sown as mixtures of species, often including a legume. It is likely that any autumn fertiliser N would reduce the ability of the legume to fix N and reduce its prime functionality within the cover crop mixture.

Table 8. Estimated demand for autumn N uptake (kg N/ha) by winter cover crops (Table 3) and median estimated autumn soil N supply (SNS) (kg N/ha) at two depths. Where the crop demand exceeds the SNS, or SNS plus N-fixation, the values are indicated in bold and underlined.

	Brassicas	Legumes	Cereals
Typical above & below-ground autumn/winter N uptake	**<u>100 (64-134)</u>**	96 (33-159)	51 (35-66)
Above and below-ground N uptake required for 50% ground cover	57	50	53
Above and below-ground N uptake required for 75% ground cover	**<u>107</u>**	95	**<u>101</u>**
Potential N supply from N-fixation	-	30-100	-
Autumn SNS (0-90 cm)	62-82		

3.3. Ability of plants to access soil nitrogen

Section 3.2 quantifies the autumn soil N supply which will be available for crop uptake. Whether or not the crop will take up this N will depend on several factors including; rooting, availability of other nutrients and plant establishment, any of which may be affected by the depth of tillage.

3.3.1. Effects of no-till on rooting

The effects of no-till on rooting of wheat and maize crops has recently been reviewed by Qin *et al*., (2017) who concluded that root growth under no-till compared to conventional tillage is variable, with both increases (Munoz-Romero *et al*., 2010) and decreases (Qin *et al*., 2004) in root length density reported under no-till compared to ploughed conditions. This may in part be driven by the length of time the site has been under no-till management; a study in New South Wales found that root length density of wheat at the seedling stage was lower under minimum tillage compared to conventional tillage for the first three years, but in the following two years it was higher than in the conventionally cultivated treatment (Pearson *et al*., 1991).

There are a range of possible causes for the different rooting responses observed between no-till and conventional conditions. One factor is the effect of no-till on bulk density, which can be increased under no-till conditions (Finney & Knight, 1973; Lampurlanés & Cantero-Martinez, 2003; Peigné *et al*., 2007). On a sandy loam site in Berkshire, England, Finney & Knight (1973) measured a lower soil bulk density in ploughed plots during the first four weeks after drilling winter wheat when compared to plots that were either direct drilled or shallow cultivated (<5 cm depth). They also found slower extension of the seminal root axes in the no-till or shallow min-tilled soil when compared to conventionally ploughed soil. Throughout the season, the root system in the reduced tillage treatments was shallower than in the ploughed treatments (Finney & Knight, 1973).

In contrast, reduced tillage can improve the survival of earthworms (Eriksen-Hamel *et al*., 2009) and may result increase the number of macropores (Martino & Shaykewich, 1994), which can provide channels through which roots can grow, potentially reducing the effects of the higher bulk density on roots (Qin *et al*., 2017). Soil type is an important factor and can control the effect of no-till on rooting. For example one study on maize rooting at a sandy loam site in Northern Italy found that the soil structure did not reach a stable architecture after two years under no-till management. The authors showed there was a negative relationship between bulk density and root development, although rooting was similar on no-till and ploughed sites (Dal Ferro *et al*., 2014). Similarly, Ellis and Barnes (1980) found that on a clay soil, direct drilling resulted in reduced root growth, but only when the soil was waterlogged overwinter, demonstrating that interactions between weather and soil type are also important.

The review suggests that there are a range of factors that can affect the ability of crops to form roots under no-till conditions, and these are often not related to the factors that control soil N supply. Soil structural condition will affect a crops ability to take up available N from the soil or following applications of manufactured fertiliser in the autumn, and so it is important to fully understand the cause of restrictions to crop growth.

3.3.2. Effects of no-till on other factors

The effect of no-till on wider issues relating to crop growth has been reviewed by various studies (Morris *et al*., 2010; Peigné *et al*., 2007; Qin *et al*., 2017; Soane *et al*., 2012), and so will not be covered in detail here. Most of these cite literature from studies outside of Western Europe. However, common themes that appear in most of the reviews which may affect the crop's response to autumn applications of fertiliser N are summarised briefly here.

No-till can result in stratification of immobile nutrients (e.g. P, K), with higher concentrations in the topmost layers (Crozier *et al*., 1999; Drew & Saker, 1980; Houx *et al*., 2011). However, this does not necessarily result in a decrease in the levels of those nutrients at lower soil depths (Rasmussen, 1999). There is some evidence to suggest that seedling establishment may be restricted by allelopathic chemicals released by residues from previous crops, which could in turn cause lower or less vigorous plant populations under min or no-till conditions where residues are left on the surface (reviewed by Morris *et al*. (2010)). Reduced soil surface temperatures on no-till soils have also been reported in both autumn (Hay *et al*., 1978) and spring (Rasmussen, 1999), as has a reduction in temperature variation (Schoenau & Campbell, 1996). These effects are thought to be a consequence of increased residues on the soil surface acting as an insulating layer, reflecting solar radiation and reducing the rate of evaporation (Morris *et al*., 2010; Schoenau & Campbell, 1996). Increased water retention in the upper soil layers may also result in reduced soil temperature under no-till conditions (Rasmussen, 1999). It has been suggested that this may slow crop emergence and development (Morris *et al*., 2010; Rasmussen, 1999) and that strip tillage may help to alleviate this effect (Morris *et al*., 2010). There are also reported increases in root-lesion and stunt nematodes under no-till, as well as increases in earthworm numbers (Thompson, 1992).

Other factors including incidence of crop pests, disease and weeds as well as a more detailed consideration of soil factors including changes in soil acidity, hydrology, water retention, deep drainage and vehicle traffic, soil biodiversity, and macro-fauna are reviewed in detail by Soane *et al*. (2012). Similarly, Rasmussen (1999) reviewed the impact of no-till on a wide range of factors under Scandinavian conditions including soil bulk density, pore volume, root development, evapotranspiration, soil water content, temperature and soil aggregate stability, nutrient and organic matter content and nitrate leaching. These factors may have an impact upon the response to autumn N via effects on the establishment of winter cereal or cover crops.

3.3.3. Effects of cultivation on crop N uptake

Even if N pools and sources vary under no-till conditions, it is ultimately the net effect on crop N uptake throughout the season and implications for yield that is of interest both financially and practically. Thomsen and Christensen (2007) applied ^{15}N labelled ammonium nitrate in the spring to plots of three winter wheat and two spring barley crops in Denmark. The study compared the effect of mouldboard ploughing (20-23 cm depth) or shallow tillage (5-10 cm depth) on the recovery of fertiliser N, total crop N uptake and yield. Yields were similar between the two tillage treatments at all three winter wheat sites, although the total N uptake and grain N content was lower at one winter wheat site under the shallow tillage treatment, which was attributed to lower concentration of grain N. Similarly, there appeared to be a lower recovery of ^{15}N under shallow tillage at one of the winter wheat sites, but the total crop N uptake (i.e. ^{15}N and non-labelled N) was the same for the two tillage systems, suggesting that there was a greater uptake of soil N in compensation. Thus, the authors concluded that there was little difference between the two cultivation methods on the uptake of spring fertiliser N at the two sites (Thomsen & Christensen, 2007).

Similarly, a study by Giacomini *et al*. (2010) in Northern France found that tillage method (mouldboard ploughing to 30 cm vs minimum tillage to a depth of 5-8 cm) had little effect on the spring applied fertiliser N dynamics in the soil and no effect on the recovery of ^{15}N fertiliser by the wheat plants. These two studies are also in agreement with a number of other studies globally on the effect of cultivation on fertiliser N recovery and soil fertiliser dynamics (Malhi *et al*., 2006; Power & Peterson, 1998; Rieger *et al*., 2008), suggesting that spring N recovery at least appears to be unaffected by the method of cultivation in the preceding autumn.

4. Evidence for effects of autumn applications of manufactured fertiliser N

There is a substantial quantity of data available world-wide on the use of no-till, but these generally reflect where the highest level of no-till adoption has occurred, e.g. the USA, South America, Canada, Australia, and China and therefore are not easily translatable to UK conditions (Derpsch *et al*., 2010). However, the hypothesis that lower yields often observed under no-till conditions may be alleviated by the application of additional N fertiliser is generally applicable to a wide range of environments. Lundy *et al*. (2015) reviewed the effect of no-till using 2759 paired comparisons of no-till and conventional tillage from 325 studies between 1980-2013 for tropical/subtropical and temperate regions on a range of crops. Whilst additional N fertiliser appeared important for improving yields in tropical/subtropical regions, in temperate regions additional N fertiliser appeared less important, explaining only 2% of the yield decline (Lundy *et al*., 2015).

4.1. Winter cereals

The level of evidence for use of autumn applications of fertiliser N on winter cereal crops in the UK has previously been acknowledged to be sparse, with limited studies carried out in the UK in the past 10 years. Most evidence on which current autumn N recommendations are made are based on studies carried out 10-30 years ago, usually under different cultivation and straw management regimes including following stubble burning (Roques *et al*., 2016). However, as part of the current review fertiliser and agronomy companies were approached to request evidence from non-published studies to obtain a more up-to-date understanding of the effects of autumn N use. There was very little data available, which perhaps is unsurprising given that application of fertiliser N is currently prohibited to tilled land after 1st September in UK NVZ zones (DEFRA, 2017). The literature search included peer reviewed and grey literature for relevant evidence and found no relevant, replicated UK studies for no-till scenarios. The search was therefore extended to include UK min-till to a depth of 10 cm and non-UK studies from countries with a similar environment to the UK. The evidence to date is summarised below.

A single non-replicated UK field trial in winter wheat found that application of 165 kg/ha of Di Ammonium Phosphate (DAP) fertiliser (18% N) at drilling under no-till conditions may improve plant number and tiller number in the following March. However, no statistical analyses were reported and without N and P controls, it is not possible to understand whether these potential benefits were driven by the application of P or N (Agrii, 2017).

A study in Denmark on three winter wheat sites and one winter barley site assessed the impact of different cultivation methods (stubble cultivating to 8-10 or 3-4 cm (min-till); direct drilling (no till), or ploughing to 20 cm (conventional ploughing)) and N rate/timings (50, 75, 100, or 125% of recommended N rate, and 100 % of recommended N rate with 15 kg N/ha of the total N applied in the autumn) on yield and grain N content (Hansen *et al*., 2011). In each case the straw was chopped and retained. In two of the winter wheat sites, yields were significantly higher in the ploughed treatment than in the direct drilled treatment, and although non-significant a similar trend was seen in the winter barley. There was no significant difference in grain yield in the autumn N treated wheat plots compared to those that received N at the standard timings (in the spring), but two of the three wheat sites had a lower % grain N content when 15 kg of the N was applied in the autumn. The yield in the winter barley was lower in the plots which received autumn N compared to those that didn't, as was the grain N %. Given these results, the authors concluded that the lower yields in the direct drilled sites were unlikely to be a consequence of reduced N availability, and instead may have been caused by other factors such as compaction (Hansen *et al*., 2011).

In a field study in NW Spain, Couto-Vázquez and González-Prieto (2016) found no effects of tillage practice (conventional ploughing and min-till) on the recovery of N in a rye-maize forage rotation. While not significant, the recovery efficiency by the rye crop of ^{15}N applied in October appeared to be half of that obtained when the fertiliser was applied in March or May. The authors proposed that this was a consequence of denitrification and nitrate leaching of N due to combination of site soil and weather conditions.

Wade *et al*. (2006) compared the effect of establishing a winter wheat crop following ploughing and reduced tillage on plant establishment, biomass and yield. An additional autumn N treatment was included where 30-40 kg/ha N was applied to a reduced tillage treatment. Across a series of three site x year experiments (9 sites in total), there was a lower plant establishment at the Rosemaund (silty clay loam, Herefordshire) in the reduced tillage treatment, a higher plant establishment at Boxworth (clay, Cambridgeshire) in the same treatment and no effect of cultivation on plant establishment at the Morley sites (sandy loam, Norfolk). While autumn application of fertiliser N at the Rosemaund site appeared to increase the plant establishment at the lowest and highest seed rates compared with reduced tillage without autumn N, ploughing still produced the highest plant establishment at each seed rate. A similar trend was seen in the GAI and crop biomass data in spring, with the Rosemaund reduced tillage sites on average having a 48% lower biomass than the ploughed treatments. In this case, autumn fertiliser N application reduced biomass production by 24%. In contrast, across the three Boxworth sites (although only significant in one year), the ploughed treatments produced 24% lower biomass than the reduced tillage sites. There was a further 10% increase in biomass in the reduced tillage treatment following autumn fertiliser N application, when compared to the reduced tillage treatment without autumn N. Across all sites, the crops appeared to compensate by increased tillering where there was lower plant establishment. Despite this compensation, there were significantly lower yields reported for all three Rosemaund sites, with, on average 1 t/ha lower yields following reduced tillage. In contrast, in two out of the three years at Boxworth, there was an average increase in yield of 0.35 t/ha following reduced tillage, and at Morley there was no significant effect of cultivation on yield in any of the three years. Application of autumn fertiliser N to the reduced tillage treatments increased yield at only one of the sites compared to the reduced tillage treatment, although there was a trend for increased yields, on average by 0.13 t/ha in eight of the nine sites, whereas at Rosemaund this value increased to 0.3 t/ha. The authors attributed the differences to the ability of a cultivation treatment to provide a suitable seed bed at a given site, demonstrated by the different responses of Rosemaund (higher yields under ploughing) and Boxworth (higher yields from reduced tillage). They also concluded that autumn applications of fertiliser N could be beneficial under reduced tillage, and particularly direct drilling. However, given the lack of autumn N treatment following ploughing in these experiments, and no spring N response treatments included to test whether the same effect could have been achieved by increasing the spring N rate, it is difficult to conclude whether or not the apparent advantage of autumn N was specific to reduced tillage or whether it was simply brought about by the total spring fertiliser N rate being sub-optimal.

Similarly, a series of 71 experiments in Denmark carried out from 1987 to 2016 under conventional cultivation found significant increases in yield following autumn application of fertiliser N in 20 cases. However, in the sites where additional spring N was applied a similar yield response was observed, leading the authors to suggest that the benefit was from the total increase in N applied rather than a benefit from timing of application in the autumn (Seges, 2017).

4.2. Winter cover crops

Research from UK conditions relating to the use of starter fertiliser on cover crops is limited, but there are a few sites which have tested this in recent years. Stobart *et al*. (2015) summarised 15 cover crop comparisons with or without 20-40 kg/ha of N as starter fertiliser across two UK sites in 2014/15. Across the sites, the mean number of plants per m^2, were very similar, regardless of starter fertiliser application. The GAI was very slightly increased (from 1.6 to 1.8) in the autumn, whereas the weed count increased in the autumn from 24 plants/m^2 to 51 plants/m^2 following the application of starter fertiliser, including a range of both broadleaf and grass weed species (Stobart *et al*., 2015). By the spring, it was difficult to see the differences between the fertiliser treatments (Stobart, 2015; Stobart *et al*., 2015).

A series of farm scale treatments were established at the Wensum Demonstration Test Catchment project site, including three treatments across an area of 143 ha: fallow with mouldboard ploughing, shallow non-inversion tillage with an oilseed radish cover crop, and direct drilling with an oilseed radish cover crop. An additional starter fertiliser (30 kg N/ha) was applied to five of the cover crop fields, whereas two sites received no fertiliser (Cooper *et al*., 2017). Significantly more

N was taken up by the oilseed radish cover crop when starter fertiliser was applied (79 kg N/ha) compared to when it wasn't (70 kg N/ha).This was driven by both an increase in biomass and total N content of the root and leaf material (Cooper *et al*., 2017). However, this means that 21 kg/ha of applied fertiliser N was not taken up and would have been at risk of leaching.

Similarly, initial results from four large plot (20x30m) demonstration trials run by Seges and established using conventional cultivation methods also indicate a trend for increased biomass and cover crop N content, although no statistics were available. Reported biomass of fodder radish and rye following the application of 40 kg N/ha fertiliser at sowing on average was 0.6 t/ha (range of 35 to 103%), and 0.5 t/ha (range of -10 to 110%) greater than the zero N control respectively across three measurement dates in October and November 2017. Associated mean increases in crop N content of 26 kg N/ha (5 to 199% range) for fodder radish and 13 kg N/ha (25 to 218% range) for rye compared to the zero N control when 40 kg of N/ha was applied at sowing (Seges, 2018). A similar trend was reported by Shah *et al*. (2015), whereby an application of 20 kg N/ha in the autumn appeared to increase biomass (fresh and dry weight) of cover crops.

Sowing date also has a large impact on the GAI achieved by October, with crops sown at the beginning of August reaching up to a GAI of 3, and crops sown in mid-September only producing a GAI of 0.5 (Stobart *et al*., 2015). It is therefore important to consider sowing date when considering the potential of cover crops to take up N. Other authors investigating autumn N fertiliser applications to cover crops concluded that sowing date had a greater influence on the growth of cover crops than early season nitrate availability (Cooper *et al*., 2017; Richards *et al*., 1996).

4.3. Environmental impacts

4.3.1. Nitrate vulnerable zone (NVZ) rules

The Nitrate Vulnerable Zones (NVZ) Action Plan Rules apply to c.60% of agricultural land in England, 16% in Scotland and 3% in Wales. Most of the UK arable area is covered under NVZ rules, which state that no manufactured fertiliser can be applied to tillage land from 1st September to 15th January (DEFRA, 2017) to prevent applications at times of year when there is a high risk of nitrogen loss

Currently, oilseed rape can receive an application of 30 kg N/ha inside the closed period for manufactured fertilisers as long as it is applied before 31st October (DEFRA, 2017). Applications to other crops during the closed period are permitted only if there is written advice from a FACTS qualified adviser. Since most winter cereal crops are sown after 1st September routine applications of manufactured N fertilisers in the autumn would require a change in the NVZ regulations.

NVZ closed periods also apply to manures with high readily available nitrogen (> 30% total N content), whereby on tillage land with sandy or shallow soils they cannot be applied on or between 1st August to 31st December, or for all other soils, 1st October to 31st January. However, there are some exceptions for crops on sandy or shallow soils, if a crop is sown on or before 15th September, manures with a high readily available N content can be applied between 1st August and 15th Sept inclusive (DEFRA, 2017).

4.3.2. Evidence for autumn N effects on nitrate leaching

Modelling nitrate leaching

The effect of autumn cultivation type on the amount of N lost by nitrate leaching was calculated using the NITCAT model (Lord, 1992). This model estimates the amount of potentially leachable N based on the previous crop and the balance between N inputs from (fertiliser and manure) and offtakes. The resulting potential leaching load is further modified according to N inputs in the autumn, mineralization of N residues from previous cropping years and autumn N uptake. Soil organic matter is one of the model inputs which influences the amount of N mineralisation. No-till is assumed to reduce N mineralisation by 15 kg N/ha compared with ploughing (Silgram & Shepherd, 1999). The model calculates the amount of nitrate N that is ‘at risk to leaching’. The amount of N leached depends on the volume of excess winter rainfall (rainfall – evapotranspiration) and the volumetric moisture content of the soil. Leaching losses will usually be greater in areas of high rainfall on free draining (i.e. sandy) soils.

Autumn crop growth and N uptake is dependent on sowing date however the model limits N uptake to a maximum of 60% of soil mineral N before winter because the model assumes that crop root density is insufficient to extract all available N during early crop growth. The maximum crop N uptake for cereals was estimated at 38 kg N/ha for crop sown 15 September and 15 kg N/ha for crop sown 15 October. The maximum crop N uptake for oilseed rape was estimated at 100 kg N/ha for crop sown 15 August and 40 kg N/ha for crop sown 15 September.

The NITCAT model was used to estimate the impact of autumn applied N (30 kg N/ha) on the risk of nitrate leaching under a range of cropping, rainfall and cultivation scenarios for 1) a winter barley cash crop following winter wheat and 2) a brassica cover crop (oilseed rape) following winter barley. The scenarios included; soil type (loamy sand and silty clay loam), over winter drainage (low - 150 mm and high – 300mm), sowing date (15 September and 15 October for the cereal cash crop and 15 August and 15 September for the brassica cover crop) and cultivation type (plough or no-till).

Effect of autumn N on winter cereal cash crop

The effect of applying autumn N to a winter barley cash crop on nitrate leaching losses is summarised in Table 9. The lowest leaching risk scenario was from early sowing (15 September), established by no-till in a low drainage area. In this scenario autumn N (30 kg N/ha) increased predicted nitrate leaching by 12 kg N/ha. This compared with increases in nitrate leaching of 15 to 17 kg N/ha when autumn N was used in the same scenario with ploughing. The highest leaching risk scenario was from a late sown crop established by ploughing (15 October) in a high drainage area. In this scenario the crop produced insufficient autumn growth, so the model predicted that virtually all of the autumn applied N was lost by leaching. The same outcome was predicted whether the soil was ploughed or no-tilled.

Effect of autumn N on brassica cover crop

The effect of applying autumn N to a brassica cover crop on the risk of nitrate is summarised in Table 10. The level of soil mineral N following winter barley is greater than following winter wheat because the winter barley was assumed to be harvested earlier increasing the potential for mineralisation to occur before planting the next crop. Table 10 shows that the lowest leaching risk was from an early sown crop (15 August) established by no-till in a, low drainage area. In this scenario autumn N (30 kg N/ha) increased the nitrate leaching by 7 to 12 kg N/ha. Ploughing made little difference to the estimated leaching losses compared with no-till. The highest leaching risk scenario was following a late sown (15 September) crop established by ploughing in a high drainage area. In this scenario the crop produced insufficient autumn growth to take up much of the autumn applied N, so the model predicted that almost all of it would have leached over winter. A similar outcome was predicted whether the soil was ploughed or no-tilled.

Conclusion

The NITCAT model predicts that autumn applied N will increase leaching even in the lowest leaching risk scenario (when crops are sown early and over-winter drainage is low). The main reason for this is that the model assumes that the crop can only take up a maximum of 60% of available N (in the soil and from fertiliser) in the autumn. This is a reasonable assumption given that the crop is establishing its root system during this period and is unlikely to achieve a root length density of one centimetre of root per cubic centimetre of soil that is necessary to extract all available water (and dissolved nitrate) from a volume of soil. An autumn N rate of 30 kg N/ha was predicted to increase nitrate leaching losses by 7 to 12 kg N/ha for cover crops or cereal cash crops respectively (under low leaching risk scenarios). If the rate of autumn applied N was reduced to 15 kg N/ha then the model predicts that the amounts of N leach would be halved.

Table 9. Estimated amount of nitrate N leached (kg N/ha) during winter following the establishment of winter barley after winter wheat.

Soil type	Drainage†	Sow date	0 Aut N Plough	30 Aut N Plough	0 Aut N No-Till	30 Aut N No-Till	**Mean**
Loamy sand	150 mm	15-Sep	15	30	9	21	**19**
Loamy sand	150 mm	15-Oct	24	52	10	38	**31**
Loamy sand	300 mm	15-Sep	16	32	10	22	**20**
Loamy sand	300 mm	15-Oct	25	55	10	40	**33**
silty clay loam	150 mm	15-Sep	15	32	11	23	**20**
silty clay loam	150 mm	15-Oct	27	46	18	36	**32**
silty clay loam	300 mm	15-Sep	23	51	18	36	**32**
silty clay loam	300 mm	15-Oct	44	73	29	59	**51**
		Mean	**24**	**46**	**14**	**34**	**30**

† Drainage equates to the excess overwinter rainfall

Table 10. Estimated amount of nitrate N leached (kg N/ha) during winter following the establishment of a brassica cover crop after winter barley.

Soil type	Drainage†	Sow date	0 Aut N Plough	30 Aut N Plough	0 Aut N No-Till	30 Aut N No-Till	**Mean**
Loamy sand	150 mm	15-Aug	20	31	14	26	**23**
Loamy sand	150 mm	15-Sep	20	41	14	27	**25**
Loamy sand	300 mm	15-Aug	21	33	15	27	**24**
Loamy sand	300 mm	15-Sep	21	43	15	28	**19**
silty clay loam	150 mm	15-Aug	19	27	16	23	**21**
silty clay loam	150 mm	15-Sep	24	42	16	33	**29**
silty clay loam	300 mm	15-Aug	31	43	25	37	**34**
silty clay loam	300 mm	15-Sep	39	68	25	53	**46**
		Mean	**25**	**41**	**18**	**32**	**29**

† Drainage equates to the excess overwinter rainfall

Literature on nitrate leaching following autumn applications of fertiliser N

Goss *et al*. (1993) reported on a series of 8 years of trials including direct drilling and ploughing treatments, as well as some where autumn fertiliser N was applied. Across all ploughed experiments, they reported that loses of nitrate between the previous harvest and spring application of nitrogen fertiliser were equivalent to 22 kg N/ha + rate of autumn fertiliser application (kg N/ha). This indicates that all of the autumn applied N leached. The straw was burnt (and subsequently shallow incorporated) on most sites. The authors concluded that reducing the use of autumn fertiliser N would make the largest contribution to reducing leaching losses from ploughed systems. The conclusions for the direct drilled plots were less clear, with no apparent relationship between autumn N applied and nitrate leached from the limited data reported. However, leaching losses were higher following an oilseed rape crop than following winter wheat, which suggests different rotations may pose varying risks to nitrate leaching (Goss *et al*., 1993).

More recently, despite increases in cover crop N content reported by Cooper *et al*. (2017), mean nitrate concentration in porous pots were increased in starter fertiliser treatments (0.8 mg NO_3-N/L) compared to unfertilised fields (0.3 mg NO_3-N/L). The starter fertiliser treated fields were all either shallow non-inversion cultivated or direct drilled, but the form of starter fertiliser used was not reported. This experiment showed there was no effect of reduced tillage compared to ploughing on the rate of nitrate leaching throughout the season, yet the nitrate leaching losses recorded in February were significantly higher from the starter fertiliser treated plots. The authors attribute this to the fact that, although there was an increase in the mean N uptake of 9.8 kg N/ha, this was much lower than the 30 kg N/ha applied, and thus the soil N contents were significantly increased at each of the 0-30, 30-60 and 60-90 cm depths. Since in this case, the aim of the cover crop was to reduce nitrate leaching, the application of a starter fertiliser was concluded to be detrimental, despite increasing biomass. Nonetheless, the use of cover crops was very effective at reducing nitrate leaching in both February and April, when compared to the fallow treatment. In the following year, the starter fertiliser used was turkey manure, so it was not possible to disentangle the effects of N from other nutrients (River Wensum DTC, 2017).

5. Conclusions

5.1. Winter Cereals

The crop demand for N uptake during the autumn was estimated at 27-29 kg N/ha for winter cereals to achieve the AHDB Growth Guide February benchmarks for high yielding winter wheat and winter barley. The median estimated supply of autumn N under zero tillage was ca. 60-80 kg N/ha, which accounts for the N supply from planted seed, crop residues, mineralisation rates and deposition from the atmosphere. This value is approximately 5-25 kg N/ha lower than reported for conventionally ploughed or min-tilled situations due to reduced mineralisation rates caused by the absence of cultivation. Based on the principles of current understanding of crop N demand and autumn soil N supply, we estimate that the majority (80-90%) of no-tilled winter cereal cash crops will have sufficient N from the soil N supply over autumn and therefore will not have a requirement for autumn fertiliser N.

There is no evidence from experiments reviewed from both industry and literature sources that autumn N application gives a unique yield response for no-till cereals. The lack of evidence mainly results from an absence of any appropriate experiments under no-till conditions and with spring N treatments to test whether any autumn N effect is unique (i.e. could not be achieved by altering spring N management). Only 15 relevant experiments were found for winter cereals of which only three (all in Denmark) included a no-till treatment. There is evidence that autumn N application can increase cereal plant populations under reduced tillage conditions. However, further research is required to identify whether spring N could be used to help the crop compensate for any reduction in plant population.

5.2. Winter Cover Crops

The majority of cover crops will also have sufficient N to achieve 50% ground cover, but a minority of cover crops will have sufficient N to achieve 75% ground cover. Whether or not autumn SNS is sufficient depends on the primary function of the cover crop. If the primary function is to reduce the risk of erosion then a ground cover of 30% or more is sufficient and there is enough autumn SNS to achieve this in the majority of situations. If the primary function is to reduce nitrate leaching then the evidence is that any autumn applied N will increase the risk of nitrate leaching because not all autumn applied N is taken up by the cover crop before winter. If the primary function is to build fertility by using a legume to fix N, then autumn N would not be advised because this will reduce biological N fixation. Achieving 50% ground cover would result in a crop N uptake of approximately 50 kg N/ha which would represent a reasonable amount of N for returning to the soil before the establishment of the following crop. However, it is not yet known what level of ground cover would be required to provide economic benefits to the following spring crop. No evidence was available on whether an autumn N application could provide an economic benefit to the following spring cash crop. There is evidence that autumn N application may increase the risk of weeds, and therefore would be detrimental to the use of cover crops to suppress weeds. There was no information available on the effect of autumn N on pest, diseases, soil structure or soil organic carbon levels. It is concluded that there is no justification for autumn applied fertiliser N to cover crops.

5.3. Environmental effects

Modelling the effects of autumn N application on nitrate leaching risk using the NITCAT model demonstrated that in **all** cases, if autumn N is applied to either cereals or cover crops, the risk of nitrate leaching is increased. However, if a crop is sown earlier, there is a smaller increase in the risk of nitrate leaching caused by autumn N. An autumn N rate of 30 kg N/ha was predicted to increase nitrate leaching losses by 7 to 12 kg N/ha for cover crops or cereal cash crops respectively (under low leaching risk scenarios). Under high leaching risk scenarios up to all of the autumn fertiliser N is predicted to be leached. The model predicted that halving the autumn N rate would half the risk of leaching, illustrating that the rate of autumn N is important.

Evidence from the literature supports the conclusions from the NITCAT model. Whilst cover crops are known to reduce nitrate leaching risk, the application of fertiliser N can result in an increase in the leaching risk, because not all of the autumn fertiliser N is taken up by the cover crop before winter. This is unsurprising given that fertiliser uptake efficiency of cash crops during the highest rates of plant growth are only around 60% for cereals and oilseed rape.

5.4. Recommendations for the Nutrient Management Guide

Overall, the review has indicated that there is insufficient evidence to change the current autumn N guidance for no-tilled winter cereal or winter cover crops. This is a consequence of there being a lack of UK data for both winter cereals and winter sown cover crops to determine whether autumn N can give a unique yield or quality improvement under no-till conditions. The principles of crop N demand and SNS suggest that there is unlikely to be a demand for autumn fertiliser N for both winter cereals and winter sown cover crops in the majority of cases. However, the lack of field based evidence means this theory cannot be tested. There are, however, clear indications that no-till conditions create a different environment for the establishment of winter cereal and winter cover crops compared to conventional inversion ploughing. **There is therefore sufficient evidence to justify research to provide evidence to support nutrient planning guidance for no-till crops.** Knowledge gaps identified in this review and recommendations for further research are outlined in Section 6.

6. Knowledge gaps and recommendations for further research

6.1. Winter cereals

- **No-till cereal management** – there is a clear lack of evidence on the interactions between several factors influenced by no-till management and crop N demand, both over the whole growing season and during specific phases of development. It will be important to first understand which factors (e.g. nutrient availability, weed/disease/pest incidence and rooting etc.) are the primary limiting factors for autumn crop development under no-till conditions. These are important knowledge gaps because i) they currently limit farmers ability to maximise productivity using no-till and ii) it is difficult to determine the need for autumn fertiliser N applications without first understanding all potential limitations to crop growth and yield under no-till conditions.
- **Environmental/leaching risks** – It is well understood that autumn applications of N increases the risk of nitrate leaching, but there is limited UK evidence at relevant scales to determine the effect of various interacting factors (e.g. cultivation method, residue C:N and quantity) on the risk of nitrate leaching.
- **Yield/quality responses to autumn N applications** – There is a lack of experimental data to answer the question whether autumn N can give a unique yield or quality improvement under no-till conditions that cannot be achieved by altering spring N management. Related knowledge gaps include; is the response to autumn N affected by the management and type of previous crop residues and soil type, should the autumn N be broadcast or placed with the seed, what is the optimum rate of autumn N and what is the mechanism by which autumn N improves yield (e.g. improved plant establishment)?

6.2. Winter cover crops

- **Effects on following spring crop** – Several studies have measured effects of autumn N on the cover crop, but there is insufficient information on the effect on the following cash crops.

6.3. Recommendations for future research

This review has identified a primary requirement for further research on no-till management systems. It is vital to first understand which factors limit crop performance under no-till conditions before focussing on one factor (e.g. N supply). Lundy *et al.* (2015) found that N fertiliser only explained 2% of the yield decline under no-till in temperate regions, and other factors are also important. Factors that need to be addressed include; soil quality, root development, nutrient availability, residue management and weed, pest and disease management. No-till systems are often cited to be to enhance soil quality when compared to conventional ploughing (Townsend et al., 2016), yet the yields achieved can be more variable (Jarvis & Woolford, 2017), and to date uptake of no-till is relatively limited (ADAS, 2015).This may be in part due to the poor understanding of how best to manage no-till systems for increased productivity and improved soil quality. There are examples of studies exploring the role of no-till and min-till under UK conditions (e.g. The Allerton Project; McKenzie et al., 2017), however if no-till is to be more widely used in the UK, more long term studies on a range of soil types, rotations and under different environmental conditions are required to provide reliable management guidelines relevant to UK growers. Both tramline trials and small plot experiments lend themselves to answering these questions, the strengths and weaknesses of each approach are summarised in Table 11.

Long-term studies are recommended as the effect of no-till and minimal cultivation methods are known to develop over many years (Soane *et al*. 2012) and are generally not adopted for short term use. These studies should include no-till and different depths of shallow min-till cultivation treatments (including strip till) across a range of UK soil types and environments. The experiments should be followed through a number of cropping seasons with a range of key assessments to determine what the limiting factors on growth and nutrient management may be under UK conditions. These could be established as long term split-field or tramline trial designs which enable the use of farm-scale cultivation equipment. Assessments and treatments could then be super-imposed on these sites. This would help to determine the long-term effects of no-till and minimal cultivation methods on yields of all crops within a rotation, as well as longer term impacts on soils and the environment. Statistical analysis may be carried out using both traditional analysis of variance and a more precise test can now be made using the ADAS initiated 'Agronōmics' approach which uses raw combine yield map data to compare the effects of treatments applied to tramlines or split-fields (Sylvester-Bradley *et al*. 2017).

Focussed experiments could be used to assess the interactions between factors of interest under no-till management. These could be super-imposed within the long-term studies described above or carried out on other fields which have not been tilled. For example testing the effect of different residue types (e.g. varying C:N ratios), nutrient availabilities (N, P, K, S etc.) or pest, weed and disease management methods under no-till conditions. This dual approach of large-scale/long-term and focussed management experiments will help to identify the primary factors limiting crop performance under no-till conditions and identify crop management approaches to help mitigate the effects of the key constraining factors.

Table 11. Strengths and weaknesses associated with small plot and tramline trials.

	Small plot trials	Tramline trials
Strengths	Able to test many treatments, inc. full spring N response.	Lower costs per trial
	Can test interactions between autumn N, spring N & autumn P	Can cover many environments/management practices
		Uses commercial drills/cultivation equipment
Weaknesses	Greater costs per trial, unlikely to be able to run at many sites	Max. 4 treatments to allow for replication
	Difficult to replicate commercial drilling conditions with experimental drills	Can't do full spring N response and calculate how much less spring N required
		Can't test 3-way interactions very robustly

7. References

ADAS. 2015. Arable Crop Report. Autumn 2015.

Agrii. 2017. Stow Longa Nutrition update - Autumn P.

AHDB. 2015a. Barley growth guide. AHDB Cereals & Oilseeds.

AHDB. 2015b. Wheat growth guide. AHDB Cereals & Oilseeds.

Balkcom K, Schoomberg H, Reeves W, Clark A. 2012. Managing cover crops in conservation tillage systems (3rd Edition). *SARE Program handbook. University of Maryland, Maryland*.

Berry P, Roques S, Clarke S. 2011a. Predicting the optimum rate and timing of nitrogen fertiliser for winter oilseed rape. . In *13th International Rapeseed Congress* Prague.

Berry P, Spink J, Foulkes M, White P. 2010. The physiological basis of genotypic differences in nitrogen use efficiency in oilseed rape *Brassica napus* L. *Field Crops Research 119, 365-373*.

Berry P, M Sylvester-Bradley R, Weightman R M. 2011b. Yield potential of combinable crops in the UK. International Fertiliser Society.

Bhogal A, Young S, & Sylvester-Bradley R. 1997. Straw incorporation and immobilization of spring-applied nitrogen. *Soil use and management* **13**:111-116.

Blake J, Bingham I, Foulkes J, Spink J. 2006. Describing and understanding barley growth and development through the use of benchmarks. HGCA Project Report No. 384.

Catt J, Howse K, Christian D, Lane P, Harris G, & Goss M. 2000. Assessment of tillage strategies to decrease nitrate leaching in the Brimstone Farm Experiment, Oxfordshire, UK. *Soil and Tillage Research* **53**:185-200

CEH. 2018. UK Deposition Data 3-year average deposition data. Centre for Ecology and Hydrology. http://www.pollutantdeposition.ceh.ac.uk/data

Cooper R J, Hama-Aziz Z, Hiscock K M, Lovett A A, Dugdale S J, Sünnenberg G, Noble L, Beamish J, Hovesen, P. 2017. Assessing the farm-scale impacts of cover crops and non-inversion tillage regimes on nutrient losses from an arable catchment. *Agriculture Ecosystems & Environment* **237**:181-193

Couto-Vázquez A, González-Prieto S J. 2016. Fate of N-15-fertilizers in the soil-plant system of a forage rotation under conservation and plough tillage. *Soil & Tillage Research* **161**:10-18.

Crozier C R, Naderman G C, Tucker M R, Sugg R E. 1999. Nutrient and pH stratification with conventional and no-till management. *Communications in Soil Science and Plant Analysis* **30**:65-74.

Cuttle S, Shepherd M, Goodlass G. 2003. A review of leguminous fertility-building crops with particular refence to nitrogen fixation and utilisation. *Institute of Grassland & Environmental Research: Aberystwyth.*

Dal Ferro N, Sartori L, Simonetti G, Berti A, Morari F. 2014. Soil macro-and microstructure as affected by different tillage systems and their effects on maize root growth. *Soil and Tillage Research.* **140**: 55-65.

Davidson E A. 1991. Fluxes of nitrous oxide and nitric oxide from terrestrial ecosystems. *In Microbial production and consumption of greenhouse gases: methane, nitrogen oxides and halomethanes.* Eds J E Rogers and W B Whitman. pp 219-235. American Society of Microbiology, Washington D.C.

Davies B. 1988. Reduced cultivation for cereals. HGCA Research Review No. 5.

Davies D B, Finney J B. 2002. Reduced cultivations for cereals: research development and advisory needs under changing economic circumstances. Home Grown Cereals Authority.

DEFRA. 2012. Review of transboundary air pollution RoTAP: Acidification Eutrophication Ground Level Ozone and Heavy Metals in the UK: Centre of Ecology and Hydrology.

DEFRA. 2017. Using nitrogen fertilisers in nitrate vulnerable zones. https://www.gov.uk/guidance/using-nitrogen-fertilisers-in-nitrate-vulnerable-zones

DEFRA. 2018. Emissions of air pollutants in the UK 1970 to 2016. Statistical release: 15 February 2018.

Derpsch R, Friedrich T, Kassam A, Li H. 2010. Current status of adoption of no-till farming in the world and some of its main benefits. *International Journal of Agricultural and Biological Engineering* **3:**1-25.

Dowdell R, Crees R, Cannell R. 1983. A field study of effects of contrasting methods of cultivation on soil nitrate content during autumn winter and spring. *European Journal of Soil Science.* **34:**367-379.

Drew M, Saker L. 1980. Direct drilling and ploughing: their effects on the distribution of extractable phosphorus and potassium and of roots in the upper horizons of two clay soils under winter wheat and spring barley. *The Journal of Agricultural Science* **94:**411-423.

Ellis F, Barnes B. 1980. Growth and development of root systems of winter cereals grown after different tillage methods including direct drilling *Plant and Soil.* **55:**283-295.

Environment-Agency. 2016. Review of Nitrate Vulnerable Zone designations for implementation in 2017 pp 1-50 Bristol UK: Environment Agency.

Eriksen-Hamel N S, Speratti A B, Whalen J K, Legere A, Madramootoo C A. 2009. Earthworm populations and growth rates related to long-term crop residue and tillage management. *Soil and Tillage Research* **104**:311-316.

Finney J, Knight B. 1973. The effect of soil physical conditions produced by various cultivation systems on the root development of winter wheat *The Journal of Agricultural Science* **80**:435-443.

Giacomini S J, Machet J M, Boizard H, Recous S. 2010. Dynamics and recovery of fertilizer 15N in soil and winter wheat crop under minimum versus conventional tillage. *Soil and Tillage Research* **108**:51-58.

Goss M, Howse K, Lane P, Christian D, Harris G. 1993. Losses of nitrate-nitrogen in water draining from under autumn-sown crops established by direct drilling or mouldboard ploughing. *European Journal of Soil Science.* **44:***35-48*.

Goulding K W, Bailey N J, Bradbury N J, Hargreaves P, Howe M, Murphy D V, Poulton P R, Willison T W. 1998. Nitrogen deposition and its contribution to nitrogen cycling and associated soil processes. *The New Phytologist* ***139:*** *49-58*.

Hansen E M, Munkholm L J, Olesen J E. 2011. N-utilization in non-inversion tillage systems. *Soil & Tillage Research* **113:** 55-60.

Hansen E M, Munkholm L J, Olesen J E, Melander B. 2015. Nitrate Leaching Yields and Carbon Sequestration after Noninversion Tillage Catch Crops and Straw Retention. *Journal of Environmental Quality* **44**:868-881.

Hay RK M, Holmes J C, Hunter E A. 1978. The effects of tillage direct drilling and nitrogen feriliser on soil temperature under a barley crop. *Journal of Soil Science* **29**:174-183.

Hodge A, Robinson D, Fitter A. 2000. Are microorganisms more effective than plants at competing for nitrogen? *Trends in plant science* **5:**304-308.

Houx J H, Wiebold W J, Fritschi F B. 2011. Long-term tillage and crop rotation determines the mineral nutrient distributions of some elements in a Vertic Epiaqualf. *Soil and Tillage Research* **112:**27-35.

Jarvis P, Woolford A. 2017. Economic and ecological benefits of reduced tillage in the UK. Game and Wildlife Conservation Trust and Fran Parkinson Agricultural Trust.

Jarvis S C, Stockdale E A, Shepherd M A, Powlson D S. 1996. Nitrogen mineralization in temperate agricultural soils: processes and measurement. In *Advances in Agronomy* pp. 187-235.

Kendall S, Holmes H, Berry P. 2017. Updating N fertiliser management guidelines for winter barley. AHDB Project Report No. 571.

Kindred D, Knight S, Berry P, Sylvester-Bradley R, Hatley D, Morris N, Hoad S, White C. 2012. Establishing best practice for estimation of Soil N Supply. HGCA Project Report No. 490.

Kumar K, Goh K. 1999. Crop residues and management practices: effects on soil quality soil nitrogen dynamics crop yield and nitrogen recovery. In *Advances in Agronomy* pp. 197-319.

Lampurlanés J, Cantero-Martinez C. 2003. Soil bulk density and penetration resistance under different tillage and crop management systems and their relationship with barley root growth *Agronomy Journal* **95**:526-536.

Lord E. 1992. Modelling of nitrate leaching. *Aspects of Applied Biology* **30:**19-28.

Lundy M E, Pittelkow C M, Linquist B A, Liang X, Van Groenigen K J, Lee J, Six J, Venterea R T, Van Kessel C. 2015. Nitrogen fertilization reduces yield declines following no-till adoption *Field Crops Research* **183**:204-210.

Malhi S S, Lemke R, Wang Z, Chhabra B S. 2006. Tillage, nitrogen and crop residue effects on crop yield nutrient uptake, soil quality and greenhouse gas emissions. *Soil and Tillage Research* **90**:171-183.

Martens D A. 2001. Nitrogen cycling under different soil management systems. *Advances in Agronomy* **70**:143-191.

Martino D L, Shaykewich C F. 1994. Root penetration profiles of wheat and barley as affected by soil penetration resistance in field conditions. *Canadian Journal of Soil Science.* **74**:193-200.

Mary B, Recous S, Darwis D, Robin D. 1996. Interactions between decomposition of plant residues and nitrogen cycling in soil *Plant and Soil.* **181**:71-82.

McKenzie B, Stobart R, Brown J, George T, Morris N, Newton A, Valentine T, Hallett P D. 2017. Project Report No PR574. Platforms to test and demonstrate sustainable soil management: integration of major UK field experiments. AHDB Cereals and Oilseeds.

Morris N, Miller P, Orson J, Froud-Williams R. 2010. The adoption of non-inversion tillage systems in the United Kingdom and the agronomic impact on soil crops and the environment—A review. *Soil and Tillage Research* **108**:1-15.

Munoz-Romero V, Benítez-Vega J, López-Bellido L, López-Bellido R J. 2010. Monitoring wheat root development in a rainfed vertisol: Tillage effect. *European Journal of Agronomy* **33**:182-187.

Nicholson F, Kindred D, Bhogal A, Roques S, Kerley J, Twining S, Brassington T, Gladders P, Balshaw H, Cook S. 2014. Straw incorporation review. HGCA Research Review No. 81.

Pearson C J, Mann I G, Zianhua Z. 1991. Changes in root growth within successive wheat crops in a cropping cycle using minimum and conventional tillage. *Field Crops Research* **28**:117-133.

Peigné J, Ball B, Roger-Estrade J, David C. 2007. Is conservation tillage suitable for organic farming? A review. *Soil use and management* **23**:129-144.

PGRO. 2016. PGRO Pulse Agronomy Guide.

Porter J R. 1993. AFRCWHEAT2: a model of the growth and development of wheat incorporating responses to water and nitrogen. *European Journal of Agronomy* **2**:69-82.

Power J, Peterson G. 1998. Nitrogen transformations utilization and conservation as affected by fallow tillage method. *Soil and Tillage Research* **49**:37-47.

Qin R, Noulas C, Herrera J M. 2017. Morphology and distribution of wheat and maize roots as affected by tillage systems and soil physical parameters in temperate climates: an overview *Archives of Agronomy and Soil Science* 1-16.

Qin R, Stamp P, Richner W. 2004. Impact of tillage on root systems of winter wheat. *Agronomy Journal* **96**:1523-1530.

Rasmussen K. 1999. Impact of ploughless soil tillage on yield and soil quality: a Scandinavian review. *Soil and Tillage Research* **53**:3-14.

Ravier C, Meynard J-M, Cohan J-P, Gate P, Jeuffroy M-H. 2017. Early nitrogen deficiencies favor high yield grain protein content and N use efficiency in wheat. *European Journal of Agronomy* **89**:16-24.

Regina K, Alakukku L. 2010. Greenhouse gas fluxes in varying soils types under conventional and no-tillage practices. *Soil and Tillage Research* **109**:144-152.

Richards I, Wallace P, Turner I. 1996. A comparison of six cover crop types in terms of nitrogen uptake and effect on response to nitrogen by a subsequent spring barley crop. *The Journal of Agricultural Science* **127**:441-449.

Rieger S, Richner W, Streit B, Frossard E, Liedgens M. 2008. Growth yield and yield components of winter wheat and the effects of tillage intensity preceding crops and N fertilisation. *European Journal of Agronomy* **28**:405-411.

River Wensum DTC. 2017. River Wensum Demonstration Test Catchment Research Update 1.

Rochette P. 2008. No-till only increases N_2O emissions in poorly-aerated soils *Soil and Tillage Research* **101**:97-100.

Roques S, Berry P, Knight S, Morris N, Clarke S, Sagoo L. 2016. Review of evidence on the principles of crop nutrient management and nutrition for cereals and oilseeds. AHDB.

Schoenau J J, Campbell C A. 1996. Impact of crop residues on nutrient availability in conservation tillage systems. *Canadian Journal of Plant Science* **76**:621-626.

Schomberg H H, Steiner J L, Unger P W. 1994. Decomposition and nitrogen dynamics of crop residues: residue quality and water effects. *Soil Science Society of America Journal* **58**:72-381.

SEGES. 2017. Autumn fertilisation for winter seed.

SEGES. 2018. Autumn N in cover crops.

Shah S, Flint C, Wilkinson S, Fletcher J M. 2015. Can cover crops justify their establishment cost and are there any potential benefits to following crops? *Getting the Most out of Cover Crops: Aspects of Applied Biology* **129***.*

Shah S, Hookway S, Pullen H, Clarke T, Wilkinson S, Reeve V, Fletcher J. 2017. The role of cover crops in reducing nitrate leaching and increasing soil organic matter. *Crop Production in Southern Britain: Aspects of Applied Biology* **134**.

Silgram M, Shepherd M A. 1999. The effects of cultivation on soil nitrogen mineralization. *Advances in Agronomy* **65**:267-311.

Sinclair A, Wale S. 2013. Nitrogen recommendations for cereals oilseed rape and potatoes *Technical Note TH651*.

Six J, Ogle S M, Breidt F J, Conant R T, Mosier A R, Paustian K. 2004. The potential to mitigate global warming with no-tillage management is only realized when practised in the long term. *Global Change Biology* **10**:155-160.

Soane B D, Ball B C, Arvidsson J, Basch G, Moreno F, Roger-Estrade J. 2012. No-till in northern western and south-western Europe: A review of problems and opportunities for crop production and the environment. *Soil and Tillage Research* **118**:66-87.

Spink J, Foulkes M, Gay A, Bryson R, Berry P, Sylvester-Bradley R, Semere T, Clare R, Scott R, Kettlewell P. 2000. Reducing winter wheat production costs through crop intelligence information on variety and sowing date rotational position and canopy management in relation to drought and disease control. HGCA Project Report No. 235.

Stobart R. 2015. Cover crops: A pratical guide to soil and system improtement *NIAB and Kellogs Origins.*

Stobart R, Morris N. 2011. Sustainability Trial in Arable Rotations (STAR project): a long-term farming systems study looking at rotation and cultivation practice. *Aspects of Applied Biology* **113**:67-74.
Stobart R, Morris N, Fielding H, Leake A, Egan J, Burkinshaw R. 2015. Developing the use of cover crops on farm through the Kellogg's Origins™ grower programme. *Aspects of Applied Biology* **129**:27-33.
Stokes D, Scott R, Tilston C, Cowie G, Sylvester-Bradley R. 1992. Effect of time of soil disturbance on nitrate mineralisation. *Aspects of Applied Biology*.
Sylvester-Bradley R, Davies D B, Dyer C, Rahn C, Johnson P A. 1996. The value of nitrogen applied to wheat during early development. *Nutrient Cycling in Agroecosystems* **47**:173-180.
Sylvester-Bradley R, Thorman R, Kindred D, Wynn S, Smith K, Rees R, Topp C, Pappa V, Mortimer N, Misselbrook T. 2015. Minimising nitrous oxide intensities of arable crop products MIN-NO. AHDB Cereals and Oilseeds Project Report No. 548.
Sylvester-Bradley R, Kindred D R, Marchant B, Rudolph S, Roques S, Calatayud A, Clarke S, Gillingham V. 2017. Agronōmics: transforming crop science through digital technologies. *Advances in Animal Biosciences: Precision Agriculture (ECPA)* **8**:728–733.
The Allerton Project. https://www.gwct.org.uk/allerton/ Accessed: April 2017.
Thompson J P. 1992. Soil biotic and biochemical factors in a long-term tillage and stubble management experiment on a vertisol 2: Nitrogen deficiency with zero tillage and stubble retention *Soil and Tillage Research* **22**:339-361.
Thomsen I K, Christensen B T. 2007. Fertilizer ^{15}N recovery in cereal crops and soil under shallow tillage. *Soil and Tillage Research* **97**:117-121.
Townsend T J, Ramsden S J, Wilson P. 2016. How do we cultivate in England? Tillage practices in crop production systems. *Soil use and management* **32**:106-117.
Van Den Bossche A, De Bolle S, De Neve S, Hofman G. 2009. Effect of tillage intensity on N mineralization of different crop residues in a temperate climate *Soil and Tillage Research* **103**:316-324.
Wade A,Spink J, Orson J. 2006. The effect of cultivation method on optimum plant population in winter wheat. HGCA Project Report No. 405.
White C, Holmes H, Morris N, Stobart R. 2016. A Review of the benefits optimal crop management practices and knowledge gaps associated with different cover crop species. AHDB Cereals and Oilseeds Research Review No. 90.