Final Report

Managing cultivations and cover crops for improved profitability and environmental benefits in potatoes

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Report Authors: Martyn Silgram and Diana Williams, ADAS
Stuart Wale and Roger Griffin-Walker, SRUC

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1. SUMMARY

1.1. Project Aims

This project focused on alleviating soil compaction, and the practical management of cover crops prior to planting potatoes. The project assessed:

- Conventional plough versus non-plough alternatives for ground preparation
- The use of cover crops prior to planting potatoes

1.2. Methodology

One English and one Scottish site on light land were studied using a randomised block design with four replicates of each treatment. In Harvest 2012, the study compared the ability of four cover crops to scavenge soil mineral nitrogen following harvest of the preceding cereal crops. After cover crop destruction in spring, the release of this “free” nitrogen (N) back into plant-available forms was assessed, together with the recovery of cover crop N by the next potato crop. In Harvest 2013, alternative methods of preparing the ground prior to planting potatoes were evaluated, including plough and non-plough options of a disc-tine-roller (Simba Great Plains DTX) and a George Moate Tillerstar. Treatment effects on soil compaction and potato crop rooting, N uptake and yield were determined. In Harvest 2014, the most promising results from the previous two seasons were combined, allowing assessments of autumn cultivation, spring cultivation, and a cover crop on soil properties, potato N uptake and yield to be made.

1.3. Key findings

- Cover crops recovered 15-80 kg N/ha otherwise be lost from light soils over-winter.
- Oil radish, winter rye and mustard all proved suitable cover crops at the English site, but oilseed rape (OSR) proved unsuitable at the Scottish site. Mustard was the most cost-effective in England; oil radish in Scotland.
- Early cover crop establishment was vital to ensure good ground cover and N uptake.
- Late cover crop destruction reduced recovery of its N by the next potato crop.
- By harvest, potatoes typically recovered 15-50 kg N/ha from cover crop residues.
- Net costs of using cover crops could be as low as +£4/ha (range +£12/ha to -£20/ha), depending on the species, seed cost and seed rate used; the establishment and destruction method; and the timing of such operations which influences C:N ratio at destruction and resulting N recovery by the potato crop. These costs may be offset through the points available for using cover crops under agri-environment schemes.
- Shallow destoning had no adverse effect on potato yield, tuber size or quality, but has the advantages of reduced draft and improved fuel efficiency.
- Rooting depths available to the potato crop following cultivations differed between the Tillerstar (20cm above stone layer), plough (20-25cm), and DTX (33-40cm), which meant that deep compaction from previous years persisted in the Tillerstar treatment. This resulted in significantly shallower depths to soil compaction ($p<0.01$) and associated shallower rooting depths 9 weeks after emergence ($p<0.01$) under the Tillerstar treatment (27cm depth) compared to the plough and DTX treatments (47-53cm depth) in Harvest 2013. Such findings were supported by soil compaction and crop rooting data in Harvest 2014.
- In spite of this evidence of the soil physical effects (penetration resistance, rooting) caused by different cultivation treatments, there was no significant difference ($p<0.05$) in use of the plough, DTX or Tillerstar cultivation methods on potato ware yield or quality, possibly due to both experimental sites being irrigated.

1.4. Practical recommendations

- Careful selection of cover crop species, seed rate and uniform crop cover are vital factors to maximise efficacy and minimise costs associated with integrating cover crop into potato rotations.
- In considering fertiliser requirements, allowance should be made for the N release from decomposing cover crop residues, which may typically contribute 30-50 kg N/ha to the next potato crop in England.
- Scottish climate requires earlier cover crop establishment (mid-Aug) than England (late Aug to mid-Sept) to ensure good ground cover and N uptake. As a result, the use of cover crops may be less well suited to Scottish conditions.
- Timely destruction is critical (ideally mid Jan to mid Feb) to promote mineralisation of cover crop residues and maximise recovery of this N by the next potato crop. Delaying cover crop destruction beyond the end of Feb is likely to result in residues not releasing N back into plant-available forms in time to match the demands of the next potato crop.
- Deep soil compaction from previous cropping or from ground preparation activities prior to planting potatoes can have a significant effect on soil bulk density, potato rooting, and associated implications for water and nutrient availability. Careful timing of tillage operations is therefore required to minimise compaction risk. Non-inversion tine-disc alternatives to ploughing can be just as effective in preparing land for planting potatoes, offering greater flexibility in operating depths, and avoiding the risk of bringing wet soil from depth up to the surface.
- Shallower destoning depths are a practical and commercially viable option to reduce draft and improve fuel use.

2. INTRODUCTION

Research on potato systems shows that deep compaction caused during ground preparation before planting (e.g. ADAS/TAG, 2005; Natural England, 2009), and shallow compaction caused by repeated traffic for spraying and irrigation post-planting (Silgram *et al.*, 2015) are two significant problems facing potato growers – with implications for yield, quality, soil structure, efficient use of irrigation, and the risk of diffuse pollution in runoff.

This project focused on alleviating compaction prior to planting, and complements allied ADAS-led Defra-funded research which focused on alleviating near-surface compaction from traffic operations between beds after potato planting (Defra project WQ0127 "MOPS2"; Silgram *et al.*, 2015). In the study reported here, the effect of ground preparation for potatoes using a conventional plough was compared to a disc-tine Simba Great Plains DTX machine and a George Moate Tillerstar. The effect of autumn cultivation in addition to spring cultivation was also explored.

In addition, this project considered the potential for the use of cover crops to take up N which would otherwise be lost via leaching over-winter when ground would be bare, and the potential for this N to be released to the next spring sown (potato) crop. This is pertinent given fertiliser prices and the agronomic need to conserve nutrients on fields where crops can access them. This also helps minimise the risk of loss to the environment via nitrate leaching - which is a relevant policy issue, such as in areas overlying sensitive aquifers in Nitrate Vulnerable Zones.

The study focused on two sites with contrasting climatic regimes on light land in England (ADAS) and Dundee (SRUC). Treatments were evaluated in a replicated, statistically robust approach over three full seasons. Over the course of the project, treatments quantified the relative merits of:

- Conventional plough versus non-plough alternatives for ground preparation
- Alternative species of cover crops to scavenge N during the autumn and winter prior to potato planting

These merits were evaluated in terms of soil compaction and structure, crop root development and the resulting N supply to and yield/quality of the potato crop. Plough, DTX and Tillerstar treatments were all fully replicated in Harvest 2013. In addition, an extra (unfunded) exploratory Tillerstar area was included at the Potato Council's request in Harvest 2014.

3. MATERIALS AND METHODS

3.1. Site selection and measurements

Two experimental sites were established: one near Dundee, Scotland and one near Telford, England. Both sites were located on loamy sand textured soils with a low stone content. The project involved three seasons of growing potatoes: Harvest 2012 (focused on cover crops prior to potato planting), Harvest 2013 (focused on plough/non-plough cultivations prior to potato planting) and Harvest 2014 (combining the most promising options from the previous two seasons).

At both sites, straw was baled and removed from the previous cereal prior to the treatments being imposed each year (winter wheat in the Telford site and spring barley in the Dundee site). No manure was applied to either site. Both sites received irrigation as required for commercial table potato crops. Initial measurements were taken at both sites each year to determine baseline soil conditions. Samples were taken during each season for:

- topsoil bulk density
- penetration resistance using manual and digital penetrometers
- root development (via pit digging) – 9 weeks after emergence
- canopy cover development
- soil mineral nitrogen (pre and post planting, at tuber initiation - TI, and 9 weeks post-emergence)
- canopy biomass for N uptake (i.e. foliar N analysis in stems and tubers) at 9 weeks post-emergence
- harvest yield and tuber characteristics (size, number, defects etc.)

3.1.1. Year 1 (Harvest 2012 season)

Sites were established using four treatments with four replicate blocks of each treatment. Seed rates used were recommended ones.

Telford

1. Control (cereal stubble)	
2. Cover crop: winter rye	seed rate 185.8 kg/ha
3. Cover crop: white mustard	seed rate 20.9 kg/ha
4. Cover crop: “hot” oil radish (variety Bento)	seed rate 25.1 kg/ha

Dundee

1. Control (stubble)	
2. Cover crop: winter rye	seed rate 186.5 kg/ha
3. Cover crop: oilseed rape	seed rate 4.48 kg/ha
4. Cover crop: “hot” oil radish (variety Bento)	seed rate 24.4 kg/ha

Seed costs*

• Rye	£0.98/kg
• White mustard	£1.60/kg
• Oil radish	in-kind contribution by Cygnet PB Ltd.(typically £4/kg)
• Oilseed rape	£10/kg

* Costs related to purchasing small quantities of seed for trial work. Purchasing larger quantities for commercial use are likely to result in lower costs due to economies of scale

At the English site, cover crops were established by drilling into stubble using a Kuhn combination power harrow with drill and discs on 21st September 2011. At the Scottish site, cover crops were direct drilled into stubble using a Duncan Mk3 Renovator seed drill on 24th August 2011. The cover crops did not receive any applied N.

Cover crops were destroyed in February 2012. Different options exist for destruction (including spraying, flailing, disking, rotovating, ploughing etc.). At the Telford site, both to promote mixing of cover crop biomass and the soil, and to help constrain management costs, but the option was taken to disc cover crops into the soil on 24 February 2012. At the Dundee site, where ground cover was more limited, the cover crops were ploughed down on 15 February 2012. The usual primary cultivations prior to bedforming were undertaken before planting in April. The area where cover crop had been grown was managed as a standard fertilised potato crop.

In addition, both sites included a large control area with no cover crop which was used for an N response trial. A total of eight different N rates were applied to the potatoes in this N response area during 2012. The different fertiliser N rates focused on lower N rates to provide greater confidence in identifying the contribution which the cover crop made to N uptake by the subsequent potato crop. Dates of key field operations are included in Appendix 1.

3.1.2. Year 2 (Harvest 2013 season)

In the 2013 season, field sites near Telford and Dundee were identified. Work in 2013 focused on methods of minimising the risk of creating subsoil compaction when preparing the ground for planting potatoes, and alleviating any compaction already present from the previous cropping. This related to the questions:

- Are non-plough options equally as effective as ploughing?
- Is it better to use several units of specialised machinery and therefore several traffic operations, or fewer passes with machinery which can perform multiple functions?
- Is there any disadvantage of shallow de-stoning?

Trial work focused on investigating alternative cultivation methods to prepare the ground prior to potato planting, specifically including the impacts of different cultivations methods on soil compaction and implications for root development, water and nutrient availability, and potential yield. The treatments explored were:

1. Plough (+ bedformer + destoner) - Deep destoning depth (Control)
2. Plough (+ bedformer + destoner) - Shallow destoning depth
3. DTX tine-disc-roller unit (+ bedformer + destoner) – Deep destoning depth
4. DTX tine-disc-roller unit (+ bedformer + destoner) – Shallow destoning depth
5. Tillerstar unit (which includes tiller/clod separater, destoner and bedformer in a single pass machine)

For the primary cultivations, operating depths were 22cm for the plough, 33cm (Scottish site) and 40cm (English site) for the Simba Great Plains DTX. For the George Moate Tillerstar, the operating depth was 28-30cm but the machine included a destoner component which meant the remaining soil depth available for potato rooting was only around 20cm. “Shallow” and “deep” destoning depths were 25cm and 35cm respectively at the English site, but 22cm and 26cm respectively at the Scottish site.

<u>All treatments were fully replicated (including the Tillerstar treatment) with four blocks of each treatment</u>. Whereas Simba Great Plains had agreed to provide equipment for

the trial as an in-kind contribution, George Moate were unwilling to do so. Eventually, a local farmer was identified with a 2-bed Tillerstar at the Telford site and a 1-bed Tillerstar for the Dundee site. The subsequent potato crops were conventionally fertilised and managed according to standard agronomic practices. Dates of key field operations are included in Appendix 1.

3.1.3. Year 3 (Harvest 2014 season)

The concept for the Harvest 2014 season was to bring together the most promising cover crop options from the Harvest 2012 work, and the most promising cultivation options from the Harvest 2013 study. The result was intended to provide a set of practical options for land management in the period between the harvest of the previous crop and the planting of potatoes the following spring. Climatic differences between the sites in Scotland and England meant that the selection of these most promising treatments differed between sites. Following discussions with the Potato Council and with the host farmers, experimental treatments were imposed at both sites according to Table 1 below (summary), and Table 2 overleaf (details).

	Autumn		**Spring**				
Treatment	DTX	Cover crop	Plough	DTX	Deep ridge	De-stone	Plant
1			X		X	X	X
2	X		X		X	X	X
3		X	X		X	X	X
4	X	X	X		X	X	X
5				X	X	X	X
6 (1 plot)			Tillerstar				X

Table 1. Treatment summary for Harvest 2014

There were five main treatments, with four replicate blocks of each treatment. In addition, an exploratory (additional unfunded) Tillerstar area was monitored which was not replicated but which was added to the planned treatments at the request of the Potato Council. A local farmer was identified with a 2-bed Tillerstar at the Telford site, whereas at the Dundee site the local dealer for the Tillerstar provided and used the equipment in preparing the ground for planting.

As in Harvest 2012, the resulting potato crops were conventionally fertilised and managed according to standard agronomic practices, and in addition a large control area where no cover crop had been grown was used for an N response trial. A total of eight different N rates were applied to the potato crop area as part of this N response trial during 2014 (English site 0, 30, 60, 90, 180, 210 kg N/ha; Scottish site 0, 15, 30, 45, 90, 180 kg N/ha). The different fertiliser N rates focused on lower N rates to provide greater confidence in identifying the contribution which the cover crop made to N uptake by the subsequent potato crop. Also within treatments 1, 2 and 5 small plots received 180 kg N/ha so that the impact of cultivation treatments could be evaluate at nil and full N rates. Dates of key field operations are included in Appendix 1.

		English site		Scottish site	
Treatment	**Cultivation treatments**	**Over-winter 2013/14**	**Cover crop seed rate ***	**Over-winter 2013/14**	**Cover crop seed rate**
1	Over-winter stubble Plough (Spring) Deep ridge, Destone, Plant	Stubble (no cover crop)	-	Stubble (no cover crop)	-
2	DTX “stubble clean” (Autumn) Plough (Spring), Deep ridge, destone, plant	Bare soil (no cover crop)	-	Bare soil (no cover crop)	-
3	Cover crop sown directly into stubble (Aug) Plough (Spring), Deep ridge, Destone, Plant	Mustard (variety Zlata)	17.5 kg/ha	Oil radish (variety Bento)	23 kg/ha
4	DTX + sown cover crop (Autumn) Plough (Spring), Deep ridge, Destone, Plant	Mustard (variety Zlata)	17.5 kg/ha	Oil radish (variety Bento)	25 kg/ha
5	Over-winter stubble DTX (Spring), Deep ridge, Destone, Plant	Stubble (no cover crop)	-	Stubble (no cover crop)	-
6	Tillerstar (1 plot) Plant	Stubble (no cover crop)	-	Stubble (no cover crop)	-

Table 2. Detailed treatment information for Harvest 2014.

* Note seed rate reduced from 22.5 kg/ha used in Harvest 2012

Treatment notes:
English site:
Plough: 20cm depth, 5 furrow reversible (150hp tractor)
DTX: as for Scottish site
Tillerstar (two-bed version, 2013 model): 30cm depth (300hp tractor) – stones buried at 20-30cm depth, leaving top 20cm of soil for crop rooting
Seed planting: 10-14 cm depth
White mustard cover crop seed cost: £1.90/kg

Scottish site

Plough: 25cm depth, 7 furrow reversible plough
DTX: tine (40cm depth) - disc (13-14cm depth)
Tillerstar (one bed version 2011/2 model)
Pre-planting depth of topsoil 42.1cm (similar to all other treatments)
Seed planting: 14cm depth
Bento oil radish cover crop seed cost: £5/kg

4. RESULTS

4.1. Harvest 2012 season

Results of an initial site survey to characterise the two sites are shown in Table 3. The previous crop was a cereal at both sites. Results show the two sites had a similar soil texture but the Dundee site had twice the organic matter content of the Telford site. The other notable differences were in *Pratylenchus* numbers which are much higher at the Telford site, and in PCN numbers which are relatively high in one of the four blocks at the Telford site. The blocking structure was applied to ensure this variability was taken into account. Penetrometer assessments pre-sowing of the cover crop (not shown) confirmed spatial heterogeneity in soil properties.

	Telford	**Dundee**
Topsoil texture	Loamy sand	Loamy sand
Topsoil pH	6.4	6.2
Topsoil P (mg/kg)	41.7 (ADAS method)	7.7 (Scottish method – Modified Morgan phosphorous method) 47.4 (ADAS method)
Topsoil OM (%)	2.5	4.4
Topsoil Total N (mg/kg)	1255	2113
Topsoil SMN (mg/kg DM)	12.2	15.4
PCN	0, 0, 10, 48	0
Trichodorus	34	94
Longidorus	5	0
Pratylenchus	1402	196

Table 3. Characterisation of the two field sites. Average values across the four replicate blocks are shown in all cases, except for PCN at the Telford site where results from each individual block are shown.

Cover crops were sown at the end of August and in early September at the two sites. Photographs showing the cover crops in winter 2011/12 are shown overleaf. At the Telford site, ground cover achieved from the cover crops was >95% in mid-January 2012 for all species , but only 45% for winter rye 26% for oil radish and < 1% for oilseed rape at the Dundee site in mid-February, having declined through winter kill.

Measurements of Soil Mineral Nitrogen (SMN) and above ground cover crop dry matter and biochemistry were taken in March 2012 using standard sampling protocols. The biochemical measurements included N content, as well as cellulose and lignin content which will influence the relative decomposability of the cover crop residues. Samples for the radish cover crop also included a separate measurement to determine the N content in the tap root.

Photographs showing cover crop establishment. Top photograph - Telford site in December 2011, oil radish (bottom left and top right), mustard (bottom right), and winter rye (top left). Lower photograph – Dundee site in January 2012.

4.1.1. English site

A summary of the key results from the English site are described below and are shown in Figure 1 and Table 4 overleaf. The cover crops proved highly effective at taking up the soil mineral nitrogen present in the soil – much of which would be residual fertiliser unused by the previous cereal crop and which would be vulnerable to leaching from such light textured soils given sufficient winter rainfall.

- Cover crop N uptake at destruction in mid-February ranged from 48-66 kg N/ha. A cover crop species effect was evident with N uptake of 66 kg N/ha (oil radish), 57 kg N/ha (white mustard) and 48 kg N/ha (winter rye). In a typical season, much of this nitrogen would have otherwise been lost from the soil via leaching over the winter months when the ground would have been left bare or in (dead) stubble.
- White mustard is not frost-hardy and died a month prior to the other cover crops being destroyed by disking. In mid-February 2012, the carbon:nitrogen (C:N) ratios at destruction, which serve as a useful indicator of the relative decomposability of crop residues were 13:1 (oil radish - stem), 20:1 (oil radish - bulb), 14:1 (mustard) and 17:1 (rye) – such relatively narrow C:N ratios would promote rapid mineralisation of the cover crop material into plant-available mineral forms. Soil Mineral Nitrogen (SMN) measurements revealed this accounted for earlier release of N by the mustard crop. The unusually wet May 2012 meant some of this mineralised N was leached below the potato root zone – which would not have happened in a more typical season.
- There was a significant effect of cover crop species on SMN at 0-30cm depth when sampled on 24 February ($p<0.001$) and 19 March ($p<0.05$), and there was still evidence of this effect persisting on 10 April ($p=0.08$). Even as late as 8 May, the effect of cover crop species was still evident on SMN levels at 30-60cm, 60-90cm and whole-profile 0-90cm depths.
- Cover crop N recovery by the next potato crop was good, with the fertiliser N response trial revealing the equivalent of around 40-55 kg N/ha from the cover crops were taken up by the potato crop (see Table 4). There was no significant effect of cover crop on potato yield ($p>0.05$).
- There was no effect of cover crop species on FLN or yield defects.

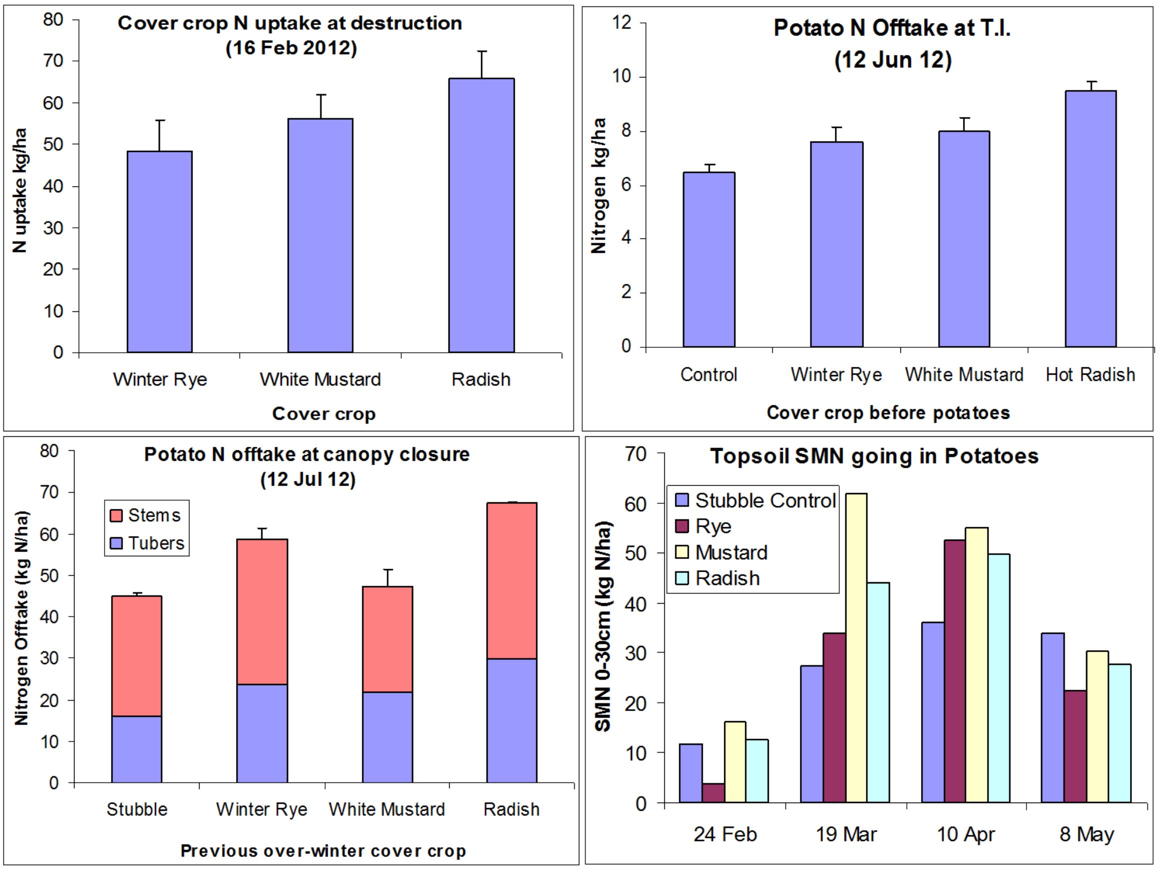

Figure 1. Cover crop N uptake at destruction, and resulting impacts on potato N uptake at TI and canopy closure under different treatments. 0-30cm depth SMN also shown.

	T/ha Yield Saleable	**T/ha Yield Total**
Green manure treatments		
Stubble control	29.1	37.0
Winter rye	36.6	44.5
White mustard	34.6	42.6
Oil radish	36.8	44.8
Fert N response (no green manures)		
Nil N	30.9	38.4
20 kg N/ha	30.0	39.5
40 kg N/ha	33.8	40.7
60 kg N/ha	37.1	45.6
120 kg N/ha	44.3	51.0
180 kg N/ha	48.9	55.9
240 kg N/ha	56.5	62.2
280 kg N/ha	60.3	64.9

Table 4. Potato yield under different fertiliser N applications, highlighting the effective N recovery by the cover crop treatment plots

4.1.2. Scottish site

- Cover crop establishment was much slower than at the English site despite late August sowing. The rapid fall in day/night temperatures meant that ground cover was never complete and the biomass limited. The OSR establishment was notably very poor.

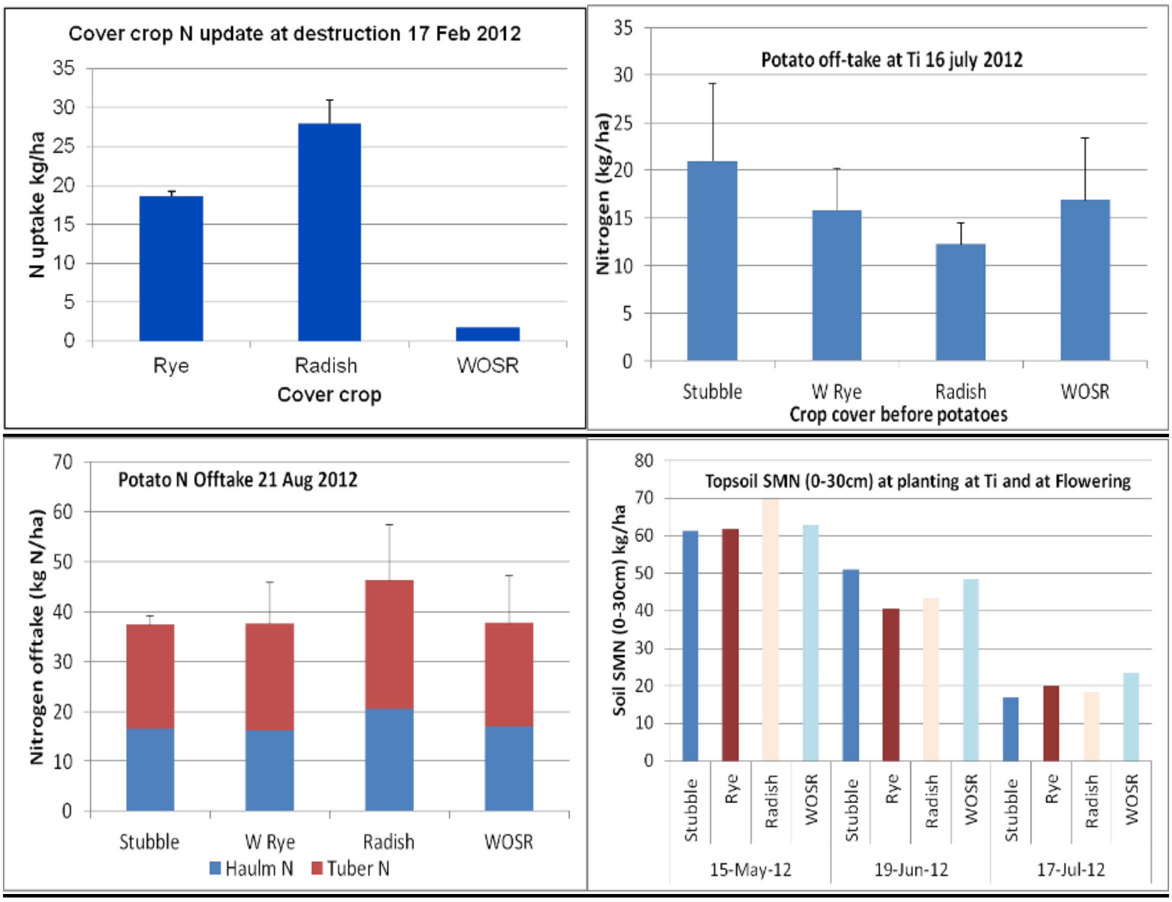

Figure 2. Cover crop N uptake at destruction, and resulting impacts on potato N uptake at TI and canopy closure under different treatments. Topsoil SMN also shown

- Cover crop N uptake at the Scottish site was much smaller, due to the colder weather over the winter months. Cover crop N uptakes at destruction in mid-February were only 19 kg N/ha (winter rye), 28 kg N/ha (oil radish), but only 2 kg N/ha (OSR) (Figure 2).
- The fertiliser N response trial revealed that 10-15 kg N/ha of cover crop N was taken up by the potato crop, with no significant effects on potato yield (Table 5).

	T/ha yield Saleable	T/ha yield total
Cover crop treatments		
Stubble	10.5	21.0
Winter rye	12.2	21.7
Radish	10.7	20.2
WOSR	11.5	20.5
Fertiliser N Response (No cover crops)		
Nil N	10.3	17.6
15 kg N	14.3	22.7
30 kg N	14.0	21.7
45 kg N	17.1	25.3
60 kg N	19.5	29.1
120 kg N	24.5	32.5
180 kg N	28.0	36.5
240 kg N	30.6	37.8

Table 5. Potato yield under different fertiliser N applications, highlighting the effective N recovery by the cover crop treatment plots

4.2. Harvest 2013 season

4.2.1. English site

There were no significant differences (p>0.05) in pH or SMN across the site prior to imposing treatments. Pre-planting soil compaction data sampled by block also showed no differences (p>0.05) across the site, with all transects showing an increase in compaction with depth.

However, measurements in mid-April after cultivation and planting operations revealed that the Tillerstar treatment had significantly greater (p<0.05) soil compaction persisting from the previous cereal harvest (Figure 3). This effect was most evident at 20.0-22.5cm depth where penetration resistance reached 2 MPa, a level which would hinder potato root development (Taylor *et al.*, 1966; Stenitzer, 1988). These results are supported by additional data from early August 2013 (Table 6) which shows that by this time the depth to maximum penetration resistance was 30-33cm in all plough and DTX treatment plots, but was only 26cm depth in the replicated Tillerstar treatment plots – and this effect was statistically significant (p<0.01).

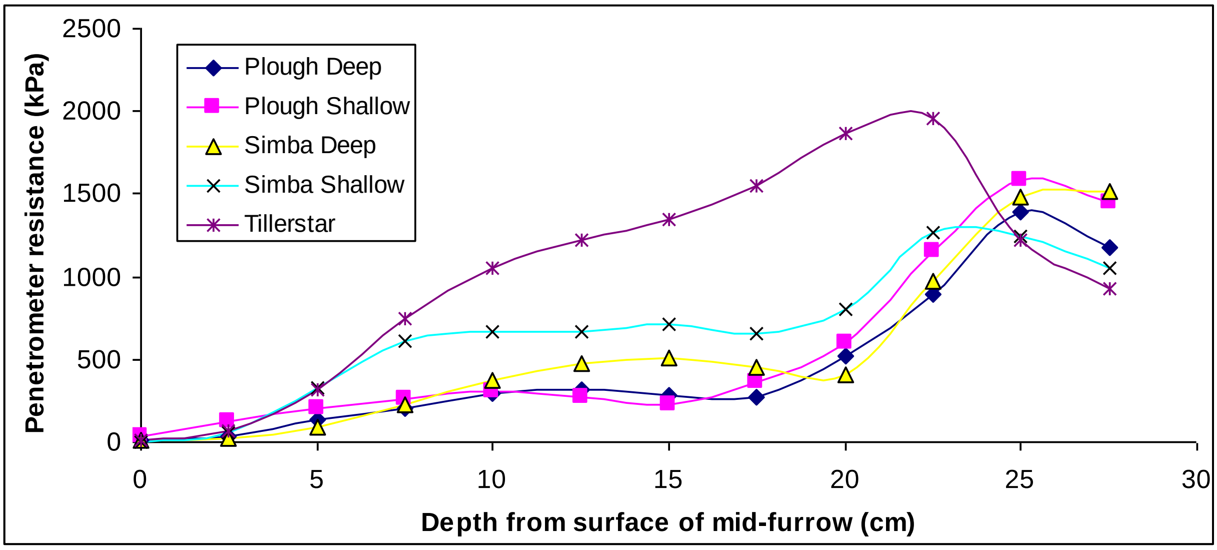

Figure 3. Post-planting soil compaction measurements under different treatments. Points are the means of replicate measurements. There was a significant effect (*p*<0.05) of treatment on soil compaction at 12.5, 15.0, 17.5, 20.0 and 22.5cm depths.

Treatment	Depth (cm)	Mean Depth (cm)
Plough Deep	32.5	
Plough Deep	32	
Plough Deep	29.75	
Plough Deep	39.5	33.4
Plough Shallow	35	
Plough Shallow	31.75	
Plough Shallow	30	
Plough Shallow	35	32.9
DTX Deep	32.5	
DTX Deep	32.75	
DTX Deep	32.25	
DTX Deep	35.5	33.3
DTX Shallow	33.25	
DTX Shallow	26.25	
DTX Shallow	32.25	
DTX Shallow	30	30.4
Tillerstar	23	
Tillerstar	27.5	
Tillerstar	25	
Tillerstar	27	25.6

Table 6. Manual penetrometer data recording depth to maximum compaction under different cultivation treatments on 9 August 2013 (replicate plot data). Depths are relative to mid-furrow bottom. There was a significant effect (*p*<0.01) of treatment on depth to maximum compaction.

Table 7 shows potato N uptake 9 weeks post-emergence on 30 July 2013. As a few plots showed an indication of PCN, results are presented both including and excluding data from those plots (shown in red). Although there were no treatment effect on soil water content or bulk density at this time, there was some suggestion of an increase in crop N uptake in the DTX shallow destoning treatment (97 kg N/ha) compared to all other treatments (80-83 kg N/ha), but this was not significant (Table 7).

Assessments of maximum rooting depth taken on 9 August reveal that potatoes growing in the Tillerstar treatment were only rooting to 27cm depth compared to 47cm for the DTX and 53cm for the plough treatments – and this effect was highly statistically significant (p<0.001) (Table 8).

Treatment	Uptake kg N/ha	Mean kg N/ha	Mean (-PCN) kg N/ha
Plough Deep	82.57		
Plough Deep	62.68		
Plough Deep	99.89		
Plough Deep	56.74	75.47	81.71
Plough Shallow	63.19		
Plough Shallow	115.58		
Plough Shallow	68.24		
Plough Shallow	51.58	74.65	82.34
DTX Deep	65.09		
DTX Deep	100.12		
DTX Deep	88.17		
DTX Deep	36.82	72.55	82.61
DTX Shallow	118.12		
DTX Shallow	87.75		
DTX Shallow	83.70		
DTX Shallow	60.97	87.64	96.52
Tillerstar	95.30		
Tillerstar	67.54		
Tillerstar	59.50		
Tillerstar	99.24	80.40	80.40

Table 7. Cultivation method and destoning depth treatment effects on potato N uptake (based on above-ground dry matter and foliar %N assessments), 9 weeks post-emergence (30 July 2013). Replicate plot data shown (red text indicates PCN-affected plots). Treatment values were not significantly different (*p*>0.05).

Treatment	Depth (cm)	Mean Depth (cm)	Mean Depth -PCN (cm)
Plough	53		
	55		
	51		
	50	52.3	53.0
DTX	40		
	50		
	50		
	50	47.5	46.7
Tillerstar	27		
	25		
	28		
	28	27.0	27.0

Table 8. Maximum rooting depths recorded in soil pits dug across potato beds 9 weeks post-emergence. Replicate measurements are shown (depths in red were plots affected by PCN; mean depths are shown including and excluding these data). There was a highly significant effect (*p*<0.001) of cultivation treatment on maximum rooting depth both including and excluding PCN-affected plots.

Three weeks after planting there was a highly significant effect ($p<0.001$) of cultivation method on mean SMN at 0-30cm depth. The smallest SMNs were measured on treatments which had been ploughed deep (82 kg N/ha) or shallow (118 kg N/ha); larger SMNs on DTX treatments cultivated deep (243 kg N/ha) and shallow (275 kg N/ha); and the largest SMNs on Tillerstar treatment plots (327 kg N/ha). This effect was still significant ($p<0.05$) when considering SMN aggregated over the entire 0-90cm depth profile. By the time of Tuber Initiation (TI), this treatment effect was still significant ($p<0.05$) at 0-30cm depth only, although it had disappeared by the time of canopy closure. There was no effect of cultivation treatment on canopy development in any of five separate assessments made during the June-August 2013 period.

Mean harvest ware yields were 51 t/ha in plough (deep destoning depth), plough (shallow destoning depth) and Tillerstar treatments, but they were notably higher (55-56 t/ha) in DTX deep and shallow destoning depth treatments although this difference was not statistically significant ($p>0.05$) (Table 9). There was no notable effect of treatment on tuber numbers.

Plot	Treatment	Deep/Shallow	Total Yield t/ha	Ware Yield t/ha	Mean Ware t/ha	Mean Ware -PCN t/ha
1	Plough	Deep	53.97	45.97		
8	Plough	Deep	62.67	53.80		
15	Plough	Deep	59.08	53.48		
19	Plough	Deep	45.56	40.41	48.42	51.08
2	Plough	Shallow	58.36	46.51		
7	Plough	Shallow	67.16	59.55		
16	Plough	Shallow	57.07	47.36		
20	Plough	Shallow	53.87	50.23	50.91	51.14
6	DTX	Deep	59.60	52.66		
10	DTX	Deep	64.52	58.16		
18	DTX	Deep	52.63	46.81		
22	DTX	Deep	28.59	23.17	45.20	55.41
5	DTX	Shallow	63.82	56.11		
9	DTX	Shallow	63.45	58.29		
17	DTX	Shallow	60.59	52.94		
21	DTX	Shallow	33.93	29.59	49.23	55.78
3	Tillerstar	Normal	55.61	49.03		
12	Tillerstar	Normal	57.94	50.04		
14	Tillerstar	Normal	58.95	53.65		
23	Tillerstar	Normal	53.73	50.22	50.74	50.74

Table 9. Cultivation method and destoning depth treatment effects on total and ware yield. Replicate plot data are shown. Right hand column shows ware yield excluding PCN-affected plots (identified in red). Treatment differences were not significantly different (p>0.05).

4.2.2. Scottish site

There were no differences in soil characteristics (chemical or physical) based on sampling and penetrometer measurements prior to imposing treatments. There was no notable PCN loading, although over 500 (Trichodorids plus *Pratylenchus*) were detected per 250g topsoil.

	Soil bulk density (g/cm^3)		
Treatment	07-Jun-13	02-Jul-13	08-Oct-13
1	1.24	0.97 a	1.16
2	1.18	0.97 a	1.09
3	1.23	0.99 a	1.1
4	1.27	1.07 b	1.09
5	1.35	1.07 b	1.14
Significance	ns	*	ns
LSD 5%	0.111	0.075	0.062

Table 10. Topsoil bulk density measurements taken during the Harvest 2013 season. Letters "ns" in this table and in subsequent tables denote no significant treatment effect

Topsoil bulk density was measured in the mid-bed furrow bottom in the centres of beds on three occasions during the growing season. Results on 2 July (Table 10) revealed significantly lower (p<0.05) topsoil bulk density in treatments 1-3 (0.97-0.99 g/cm^3) compared to shallow destoning DTX and Tillerstar treatments 4 and 5 respectively (1.07 g/cm^3).

This effect is consistent with crop root development results from July 2013, which indicated notably less well developed rooting in the Tillerstar plots. Mean rooting depth was 45-46cm on treatments 1 and 3 but only 41cm on Tillerstar treatment 5, while mean rooting width was 70-73cm on treatments 1 and 3 but only 62cm on Tillerstar treatment 5.

However, this apparent constraint on root development at a critical phase of growth did not appear to adversely affect the recovery of nitrogen from the soil. There was no discernible effect of treatment on foliar N content (4 July 2013), and potato N uptake 9 weeks after planting showed higher N uptake both in the shallower destoning treatments and in the Tillerstar treatment (Table 11).

	Treatment	Depth	N uptake Kg/ha	SD uptake
1	Conventional	Deep	30.86	8.65
2	Conventional	Shallow	37.62	4.46
3	DTX	Deep	31.61	6.59
4	DTX	Shallow	45.81	4.32
5	Tillerstar	-	40.17	2.44

Table 11. Nitrogen uptake in the haulm 9 weeks after planting

At harvest, there was a trend for slightly higher yields under shallower destoning treatments, with conventional ploughing treatment yields of 51.7 (deep) and 55.3

(shallow) t/ha, and DTX yields of 51.5 (deep) and 53.6 (shallow) t/ha, although this was not statistically significant (*p*>0.05; Table 12). The yield from the Tillerstar area was 51.3 t/ha, similar to the lower yields recorded on the deeper destoning depths for plough and DTX treatments. There was also a notable trend for fewer tuber numbers with the Tillerstar treatment (659,000/ha) compared to the other four treatments (702,000-747,000/ha). There were no significant differences (*p*>0.05) in yield or tuber numbers (either total or by size fraction) between the different cultivation treatments, with mean treatment yields of 51-55 t/ha across the five treatments.

	Treatment	Tuber size fraction				
		< 45mm	45-65mm	65-85mm	> 85mm	Total
1	Conventional - Deep	2.8	32.5	16.3	0.5	51.7
2	Conventional - Shallow	2.8	34.7	17.7	0.1	55.3
3	DTX – Deep	2.5	34.4	14.0	0.5	51.5
4	DTX – Shallow	3.0	32.6	17.7	0.4	53.6
5	Tillerstar	2.5	31.6	17.0	0.3	51.3
	Significance	ns	ns	ns	ns	ns
	LSD (5%)	1.26	6.96	5.90	0.67	8.14

Table 12. Harvest yield for different treatments, in total and by tuber size fraction

4.3. Harvest 2014 season

4.3.1. English site

Photographs: Cultivation and cover crop treatments at the English site

Cover crop N uptake was high at the Telford site, with 80-98 kg N/ha recovered from the post-cereal harvest soil – most of this nitrogen would have otherwise been lost from the land given sufficient drainage over-winter (Table 13). This reflected the warm, reasonably moist conditions over the September-February period when the cover crop was in place. There was a consistent significant effect ($p<0.05$) of treatment on both cover crop C:N ratio and N offtake, with narrower C:N ratios and greater N offtakes observed where the cover crop had been planted after autumn DTX cultivation (Table 13). This evidence indicates that this cover crop established better following autumn cultivation rather than planted directly into cereal stubble.

However, whereas in year 1 (Harvest 2012) the frost had killed the mustard in February – avoiding the need for any additional destruction activities – in Harvest 2014 season there was no significant frost in the January to March period. Consequently, the mustard continued to develop and its carbon to nitrogen ratio widened as the crop became more "woody" (Table 13). This is important as the wider C:N ratios become, the greater the relative proportion of lignin and other slowly decomposing biochemical fractions, and therefore the slower the N release (mineralisation) occurs back into plant-available forms of nitrogen to benefit the following crop. In hindsight, the cover crop should have been destroyed in February. However, due to the lack of any notable frost, the cover crop was finally destroyed by flailing in mid-March 2014, four weeks later. Consequently, at destruction the C:N ratio had reached 19:1 to 22:1 – which previous research has shown can lead to initial immobilisation of nitrogen in the soil with the release of the cover crop N into plant-available forms being delayed for some months (e.g. Harrison & Silgram, 1998; Silgram & Harrison, 1998). This late destruction could delay the recovery of the cover crop N by the next potato crop, as more of the nitrogen would either be released into plant-available forms later on and/or contribute to organic matter reserves (useful in light textured, poorly bodied soils).

Treatment Number	Treatment Description	N offtake kg/ha Jan 14	C:N Ratio	N offtake kg/ha Mar 14	C:N Ratio	Crop growth stage at flailing
3	Cover crop into stubble	72.1	16.1	80.8	21.8	Flowering
4	Cover crop after DTX cultivation	94.6	12.2	97.8	19.1	In Bud

Table 13. Cover crop N offtake in January and March 2014

In March 2014, there was evidence that SMN was lower in cover crop treatments 3 and 4 (both 22 kg N/ha) compared to treatments 1, 2, and 5 (33-42 kg N/ha). This effect was evident at 0-30cm ($p<0.01$), 30-60cm ($p<0.05$), 60-90cm ($p<0.001$) and whole profile (0-90cm) ($p<0.001$) depths, and would be expected as a result of the SMN being scavenged over-winter by the growing cover crop. However, the opposite was true by June 2014, as the mineralisation of the cover crop residues resulted in significantly higher ($p<0.05$) ammonium-N at 0-30cm depth (4.4-4.9 kg N/ha for cover crop treatments 3 and 4 respectively, but only 3.8, 4.1 and 3.4 kgN/ha in treatments 1, 2 and 5 respectively). Both ammonium-N and nitrate-N are plant-available, but the mineralisation of organic material, such as cover crop residues, initially produces ammonium N before the process of nitrification occurs, and this explains the elevated ammonium levels which were only observed in the cover crop treated plots. This evidence is consistent with the unusually wide C:N ratio of the cover crop at destruction limiting plant-available N during March, but ultimately increasing mineral N supply later in the season in June. In hindsight, destroying this cover crop earlier would have promoted earlier release of this plant-available N which would have been better timed with the N demands of the potato crop.

By nine weeks post-emergence in July 2014, 0-90cm depth SMNs were 43, 50, 60, 48, 42 kg N/ha for treatments 1-5 respectively, with only the slightest indication of a trend (p=0.10) for the cover crop treatments 3 and 4 to have higher values than the other treatments due to the mineralisation of their residues, suggesting the potato crop was utilising this additional source of readily-available N. Comparable measurements in July 2014 for the Tillerstar area recorded SMN of 58 kg N/ha, substantially higher than all the other non-cover crop treatments.

Post-harvest data from September 2014 showed that SMN at 60-90cm depth was significantly (p=0.01) higher under the control plough treatment 1 (16 kg N/ha) and Tillerstar treatment 6 (18 kg N/ha), compared to the cover crop treatments 3 and 4 (both 12 kg N/ha), again suggesting the hypothesis that the more labile, mineralised cover crop N had been more efficiently recovered by the potato crop compared to SMN solely derived from indigenous soil organic matter.

Pre-harvest assessments of soil compaction in Figure 4 revealed substantially greater compaction at 22.5cm (p<0.05), 25.0cm (p=0.08) and 27.5cm (p=0.01) depths under the Tillerstar (Treatment 6) compared to the plough (Treatment 1) and DTX treatments (Treatments 2 and 5). This finding was also reflected in the significantly (p<0.05) shallower (20cm) depth to which thick roots were detected in the Tillerstar area compared to the DTX/Plough, DTX/CC/Plough and stubble/DTX treatments receiving comparable levels of fertilisation (Table 14). These results are consistent with those reported in Harvest 2013 (Tables 6 & 8). Such differences may reflect the contrasting depth of soil available for rooting which resulted from cultivation treatments using the DTX (40cm depth) or Tillerstar (20cm above stone layer) machinery. Also notable was a trend regarding the maximum depth to which thick roots were detected (p=0.08), with plots with DTX cultivations in autumn (Treatments 2 and 4) having thick roots reaching greater depths (26.3-27.5cm) compared to treatments which were not cultivated until spring ploughing (21.3-23.8cm), and this effect was irrespective of whether a cover crop was grown over-winter (Table 14).

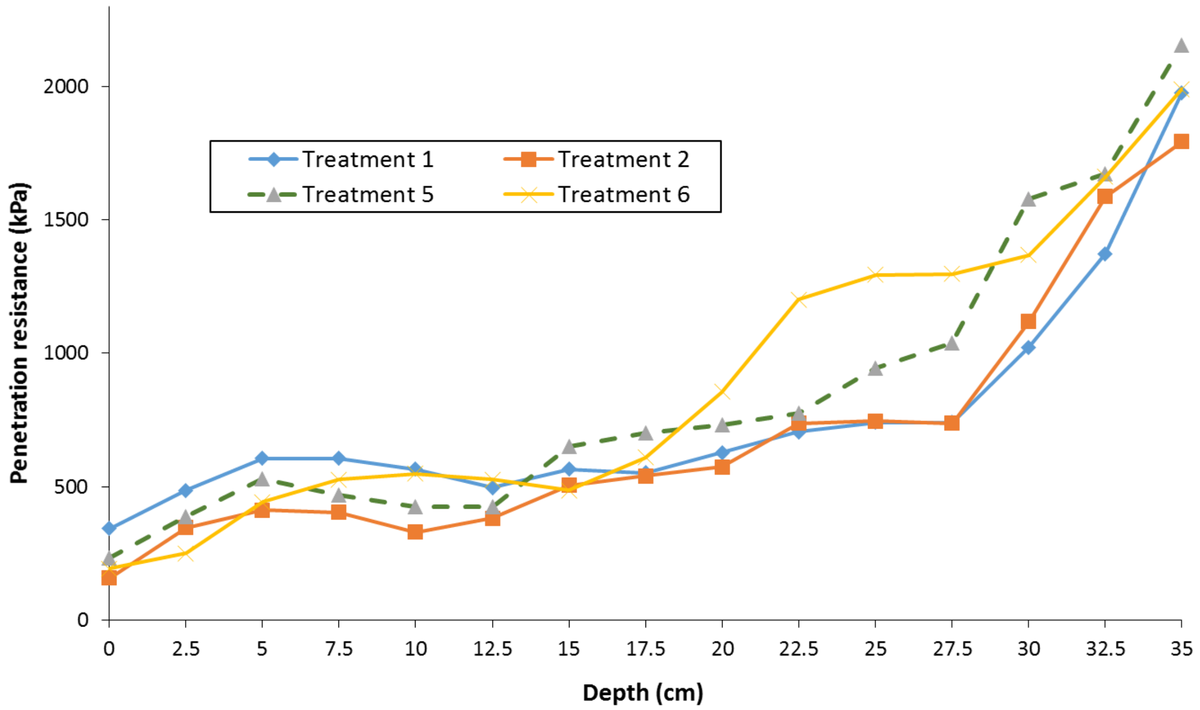

Figure 4. Digital penetrometry measurements from non-cover crop treatments, pre-harvest 2014. Treatment codes are defined in Table 14 below.

Treatment Number	Treatment Autumn	Treatment Spring	Nitrogen Rate	Depth to Subsoil cm	Thick Roots Depth cm	Fine Roots Depth cm
1	Stubble	Plough	Nil	48.75	23.8	41.7
2	DTX	Plough	Nil	46.25	27.5	45.0
3	CC in stubble	Plough	Nil	48.25	21.3	47.5
4	DTX + CC	Plough	Nil	48.75	26.3	47.5
5	Stubble	DTX	Nil	47.5	21.7	37.5
5	Stubble	DTX	180	45	40.0	>45.0
6	Stubble	Tillerstar	Nil	45	20.0	45.0
6	Stubble	Tillerstar	210	45	20.0	45.0

Table 14. Potato rooting assessments in soil pits, July 2014

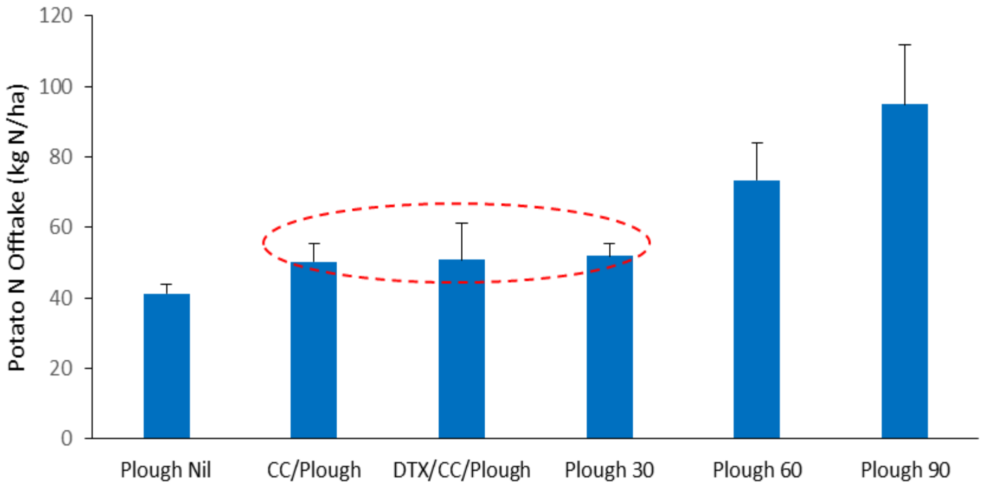

Figure 5. Potato N offtake at canopy closure for plough treatments receiving different fertiliser N rates (30, 60 and 90 kg N/ha) in the N response plots, and potato N offtake where cover crops had been grown with nil N applied to the potato crop (CC). Bars represent the means of four replicates. The dotted line highlights the means of the three bars which were not statistically different (*p*<0.05).

By July 2014, potato biomass sampling at canopy closure revealed that the cover crop treatments had captured 30 kg N/ha compared to uptake on the nil N plots (Figure 5). At harvest in mid-September 2014, Figure 6 shows there was no significant effect ($p>0.05$) of replicated Plough, DTX/Plough and DTX treatments on total or ware tuber numbers, or on total or ware yields (45-85mm). However, there was evidence ($p<0.05$) of slightly higher yields of the 45-65mm tuber size fraction in the DTX/Plough compared to the Plough treatment at 45-65mm, but this effect was reversed ($p<0.05$) in the 65-85mm tuber size fraction. The additional unreplicated Tillerstar area recorded lower total and ware tuber numbers at 210kgN/ha compared to the equivalent plough treatment, but higher total and ware yields at nil N and 210 kg N/ha rates – this result appears anomalous as it was not found at either the Scottish site this year, or at either site in the fully replicated Tillerstar treatment studied in Harvest 2013 - so caution is required in its interpretation (Figure 6).

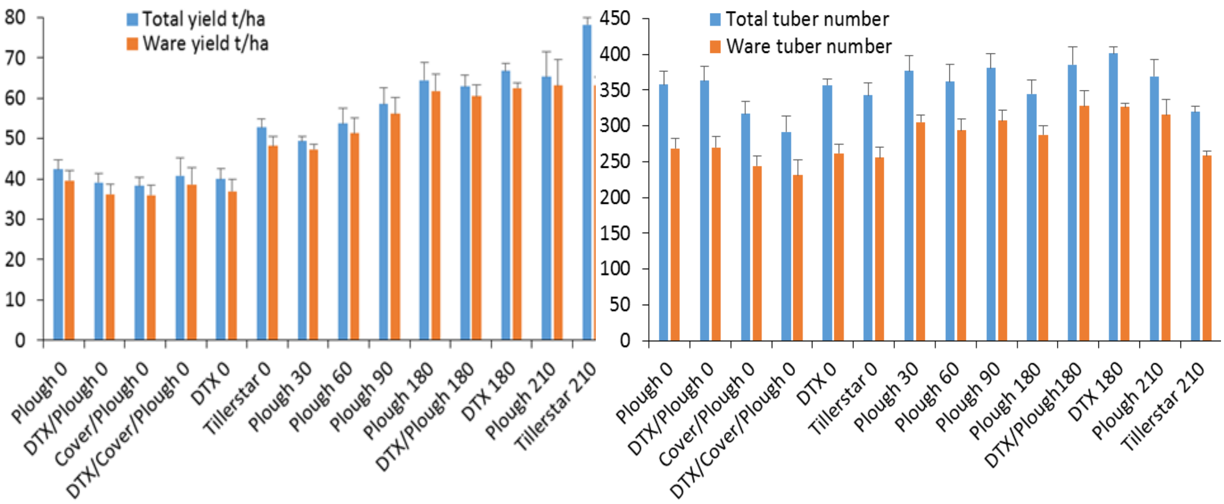

Figure 6. Harvest yields in t/ha (left) and tuber numbers in thousands per hectare (right) for different treatments. Numbers on x-axis labels refer to different fertiliser rates (kg N/ha) applied to the potato crop in N response plots. Standard errors are shown.

4.3.2. Scottish site

Although sown on 2 September, the cover crop of oil radish again failed to achieve complete ground cover and a substantial biomass. However, because of a milder autumn and winter the cover crop reached 80-90% ground cover by early January, and at destruction on 12 January 2014 had an N offtake of 20.1-20.7 kg N/ha and a C:N ratio which ranged from 9.6:1 to 10.8:1. This narrow C/N ratio is likely to have encouraged the rapid mineralisation of the cover crop N into mineral forms available to the next potato crop. There was no effect on cover crop establishment or chemical characteristics at destruction from the use of the DTX in the autumn prior to drilling of the cover crop (i.e. comparing treatments 3 and 4).

There was no effect of the cover crop treatment on FLN populations based on soil assessments prior to planting potatoes. There was no notable effects of cultivation or cover crop treatment on soil compaction post-planting or 9 weeks after emergence; or on potato rooting distributions sampled in early July 2014. However, Figure 7 shows that penetrometry measurements immediately prior to harvest did indicate greater compaction at 27-35cm depth under the Tillierstar treatment compared to treatment 1 (plough control), treatment 2 (Autumn DTX, Spring plough) and treatment 5 (DTX Spring). This measured compaction in the Tillerstar treatment exceeded 2 MPa which Taylor *et al.* (1966) and Stenitzer (1988) reported was a level at which that the number of roots penetrating soil was substantially reduced, with measurements peaking at 3 MPa which Håkansson & Lipiec (2000) regarded as the critical penetration resistance which prevented root penetration.

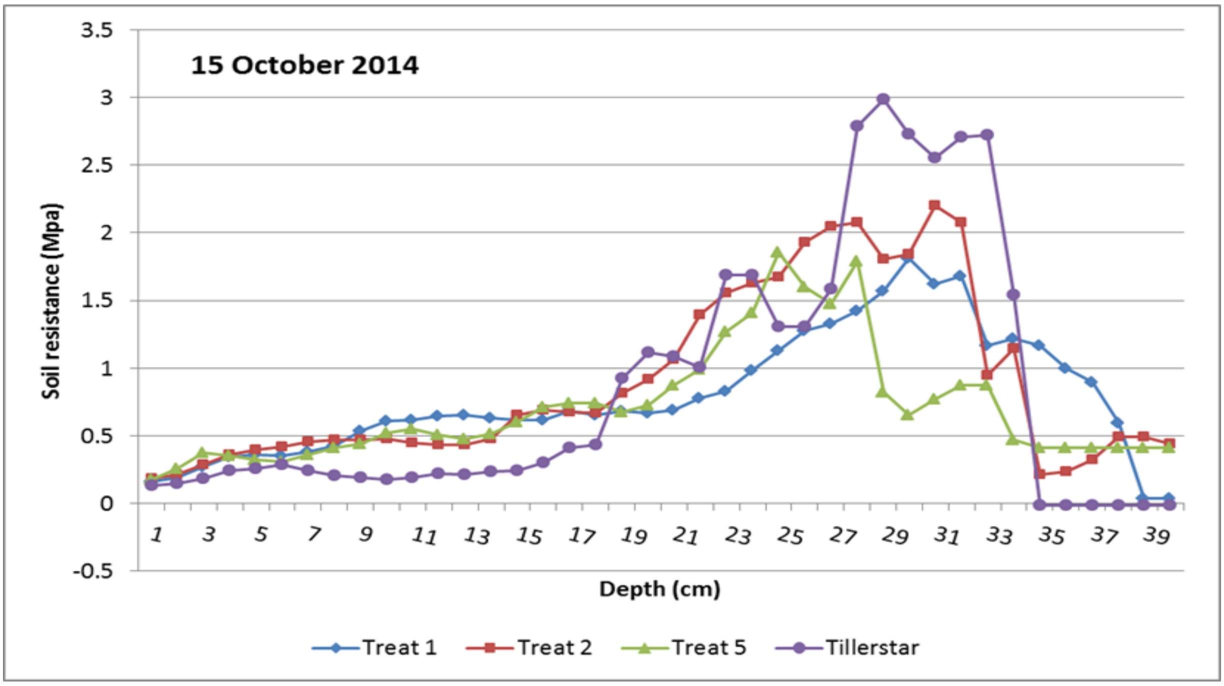

Figure 7. Penetrometry measurements for different treatments prior to harvest

There were no significant differences between foliar and tuber N offtake from different treatments in July or in September 2014. At harvest in October 2014, in spite of the higher cover crop seed rate used compared to the harvest 2012 season, and the greater ground cover reached by the cover crop prior to destruction, results indicated that a similar amount of cover crop N to the harvest 2012 trial - only around 10 kg N/ha

- was recovered by the subsequent potato crop. This is substantially less than that found at the English site in both harvest years 2012 and 2014.

There was evidence of a lower yield (30.3 t/ha) in the Tillerstar treatment compared to treatments 1-5 where yields were 39.8-44.7 t/ha (Table 15). Similarly, results indicated fewer tuber numbers in the Tillerstar treatment (308,300 tubers/ha) compared to treatments 1-5 (which had 312,600-342,200 tubers/ha) (Table 16). However, the Tillerstar area was unreplicated and so results under this treatment should be interpreted with caution. In contrast, none of the replicated cultivation treatments (1-5) had a significant effect on either yield or tuber numbers (Tables 14 &15).

	Yield (t/ha)				
Treatment	**<45mm**	**45-65mm**	**65-85mm**	**>85mm**	**Total**
1	3.40	30.59	8.09	0.12	42.2
2	3.49	31.38	7.35	0.12	42.3
3	3.32	34.13	7.25	0	44.7
4	2.63	31.53	9.20	0	43.4
5	4.00	31.43	4.36	0	39.8
LSD	0.996	4.727	5.663	0.244	8.84
Sig.	ns	ns	ns	ns	ns
Tillerstar	4.60	24.6	0.8	0.4	30.30

Table 15. Harvest yield by tuber size fraction and total yield for different treatments

	Tuber numbers (000's/ha)				
Treatment	**<45mm**	**45-65mm**	**65-85mm**	**>85mm**	**Total**
1	75.9	225.2	28.9	0.2	330.2
2	81.6	229.5	26.5	0.2	337.9
3	71.1	245.2	26.0	0.0	342.2
4	56.8	224.0	31.8	0.0	312.6
5	85.0	241.3	14.2	0.0	340.6
LSD	26.91	30.86	18.93	0.49	42.06
Sig.	ns	ns	ns	ns	ns
Tillerstar	93.4	211.0	2.9	1.0	308.3

Table 16. Tuber numbers at harvest by size fraction and totals for different treatments

5. Discussion

5.1. Cover crops: potential benefits

Cover crops have the potential to scavenge substantial quantities of valuable unused residual fertiliser N and indigenous mineral N, which would otherwise be vulnerable to leaching from soils in drainage water over the winter months when the ground is left bare or in (dead) stubble prior to preparing ground for potatoes in the spring. Previous ADAS research has shown that such cover crops can capture up to 100 kg N/ha, depending on planting and destruction dates, cover crop species and seed rates, prevailing weather conditions, and soil type (e.g. Harrison & Silgram, 1998; Silgram & Harrison, 1998).

Although these cover crops will only release a proportion (typically around one third to one half) of this N scavenged from soils over-winter (Harrison & Silgram, 1998; Silgram & Harrison, 1998), the remaining cover crop N still has notable agronomic value, as it helps to build up the pool of labile (i.e. readily mineralisable) soil organic matter, which in turn will assist in decreasing soil bulk density and improving water retention characteristics (Hanza & Anderson, 2005). The tap roots found in brassica cover crops such as fodder radish (rather than the more fibrous roots found in rye) have been found to benefit root penetration into soils growing maize (Chen & Weil, 2011), and are therefore recommended by Chen *et al.* (2014) as providing a better soil environment for the growing of subsequent cash crops in the USA. Sainju *et al.* (2007) concluded that cover crops will improve carbon sequestration more rapidly in irrigated crops, while Cuttle *et al.* (2003) noted that there are additional secondary benefits such as improved soil aggregate stability which is driven by the turnover of young fresh organic matter.

5.2. Cover crops: efficacy

Cover crops established well at the English site, with good ground cover using all three species. The cover crop N taken up by the next potato crop was considerable (typically 50-80 kg N/ha), and suggests growing over-winter cover crops in central and southern England can serve as a beneficial agronomic practice by effectively scavenging mineral N which would otherwise be lost via leaching when ground was left bare (or with dead stubble) during the winter drainage period. Such unused residual fertiliser from the previous crop can be considerable – as often only around 60% of the fertiliser applied to a winter cereal crop remains in the soil at harvest (Defra, 2010). There was no evidence of any negative effects of the use of cover crops (e.g. increased slug activity) in any of the experimental plots at either of the two sites.

Cover crops established less well at the Scottish site. It would seem that differences in ground cover and establishment were primarily a function of soil temperature. The cooler autumn and winter conditions may make cover crops a less viable option for Northern Britain, although earlier sowing of cover crops (i.e. immediately after the previous crop's harvest in mid-August or broadcasting into the previous cereal crop pre-harvest), combined with the use of a higher cover crop seed rate, may help overcome these climatic constraints.

Operationally, one negative factor is the cost of cover crop seed, and the time/fuel spent in sowing and destroying the cover crop. In practice, seed costs can be minimized e.g. by using tailcorn or bulk-buying such seed, while destruction costs can be avoided entirely by using the cultivations necessary to prepare the ground for potatoes (e.g. ploughing) or can be minimized by using a cover crop, such as mustard, which is not frost hardy.

Of all the cover crops evaluated, white mustard and oil radish were the most effective cover crops at the English site, but white mustard proved easier to destroy as it is not frost-hardy. However, the lack of a sufficiently strong frost in the final year of the trial meant that this mustard survived for too long, resulting in an over-mature cover crop. This cover crop had a wide C:N ratio of around 21:1 (Table 13). As a result, although the cover crop in Harvest 2014 had over 80 kg N/ha at destruction, only 30 kg/ha was released into plant-available forms in time to be taken up by the next potato crop. In contrast, in the Harvest 2012 trial, although the mustard cover crop only contained 57 kg N/ha, it was destroyed earlier when its C:N ratio was only 14:1, resulting in around 50 kg N/ha of this cover crop N being recovered by the following potato crop. This demonstrates the importance of timely destruction of cover crops in January or February, before their maturity limits the speedy decomposition of their residues in time to supply N to the next potato crop. Establishing the level of release of N from the cover crop will be important in deciding how much N to apply to the succeeding potato crop.

In contrast, the cooler climate meant mustard was not a suitable choice of cover crop in Scotland, and a cover crop of oilseed rape also established poorly (in the absence of starter N). Oil radish (which also did well at the English site) proved the most appropriate choice in Scotland. This, together with the wide range of different levels of cover crop N uptake at destruction (varying from <15 kg/ha in Scotland to >80 kg/ha in the final season at the English site), highlights that climate, cover crop species and seed rate are three critical factors affecting the viability of cover crops in different locations/seasons. Only a limited number of cover crop species were studied in this project, although many others are available.

Another key factor in the success of a cover crop in capturing soil N and releasing it to the subsequent crop, is uniformity of cover crop ground cover across a field. If a potato grower is going to rely on release back to the succeeding potato crop to moderate fertiliser N applications then confidence is needed that this cover crop N release will be even across the whole field area. Thus conditions suitable for germination and growth of the cover crop must be available at and after the time of sowing. In dry autumn conditions, there may be patchy cover crop establishment and development, and this could hinder accurate determination of N application requirements for the next crop.

At the English site, there was also evidence that the Autumn DTX treatment was associated with increased cover crop N uptake measured both in January and in March, compared to where the cover crop had been drilled directly into cereal stubble (Table 13). This is likely to be the result of the greater loosening of the soil from the DTX stimulating soil N mineralisation (e.g. Silgram & Shepherd, 1999) as well as promoting seed establishment and root development in the autumn months.

5.3. Cover crops: costs

Costs of growing cover crops comprise two components: seed costs and establishment (drilling or broadcasting) costs. Destruction costs can be avoided (e.g. by using frost-sensitive species) or minimised as cultivations are always required in February or March anyway (e.g. to incorporate cereal stubble and/or loosen compacted subsoil) to prepare the ground for planting potatoes. Seed costs can be significant but can be minimised by selecting species with less expensive seed or by using free tailcorn, and by using the lowest seed rate which is sufficient to establish good ground cover.

Cover crop N offtake at destruction (kg/ha)	Fertiliser value of cover crop N (£0.78/kg N)	Cost of cover crop seed * (£1.60/kg; 17.5kg/ha)	Cost of drilling	Net cost (-) or benefit (+)
30	£23	£28	£15	- £20
50	£39	£28	£15	- £4
70	£55	£28	£15	+ £12

Table 17. Example costs for white mustard at the English site, showing the effect of different example cover crop N recovery at destruction. The cover crop scavenged 57 and 81-98 kg N/ha at destruction in Harvests 2012 and 2014 respectively. Equivalent recoveries of cover crop N by the next potato crop were 50 and 30 kg N/ha respectively, highlighting the importance of the different cover crops' C:N ratios at destruction (only 14:1 in Harvest 2012 but around 21:1 in Harvest 2014).

* 2012 seed costs relate to purchasing small quantities of seed for trial work. Purchasing larger quantities for commercial use may result in lower costs due to economies of scale

Under good conditions in Central England, if cover crops recover 50 kg N/ha (worth £39 assuming fertiliser N costs of £0.78/kg) – as found in the first year's trial in England (Table 1; Figure 4) with seed costs of £1.60/kg x 17.5 kg/ha = £28/ha (white mustard), and with drilling costs of around £15, there is a small net cost of around £4/ha of using cover crops before potatoes (Table 17). However, this calculation is highly sensitive to fertiliser price, cover crop seed cost and cover crop rate applied. A small reduction in any of these variables would render the use of cover crops "cost neutral". Cover crop seed costs can be reduced by reducing seed rates, obtaining cheaper seed (perhaps of a different species), or by supplementing purchased seed by using free tailcorn. Based on these trials, it is likely that a more modest seed rate (15kg/ha instead of 17.5kg/ha) would still prove effective in establishing a cover crop with a good ground cover in England (it was reduced between Harvest 2012 and 2014 years in this study with no effect on cover crop N uptake), and this is a realistic way to make cover crops cost-neutral under English conditions. Further work could assess the efficacy of different seed rates for different cover crops species, and the practical use of tailcorn to supplement purchased cover crop seed, and assess exactly how this propagates through to operational net costs or benefits.

However, in more suboptimal climate conditions in Scotland, the oil radish cover crop seed costs and application rates were greater than those in England, costing £4/kg x 25kg/ha = £100/ha, while cover crop N recovery was much smaller at only 15kgN/ha, resulting in a much higher net cost of growing a cover crop of £103/ha. The difference between the costs of the cover crop at the English and Scottish sites highlights both the importance of choosing cheap cover crop seed, and the conclusion that cover crops are a less viable option in the cooler Scottish climate where poorer uptake of N and possibly slower decomposition of cover crop residues is likely to limit the proportion of the cover crop N which is mineralised and made available to the next potato crop.

In spite of the small cost of around £4/ha for cover crops in England (Table 17), the additional benefit of increasing soil organic matter reserves, with associated improvements in soil structure and water holding characteristics means the option of using cover crops before potatoes remains a viable option in England, especially on poorly structured, light textured soils and in areas overlying sensitive groundwaters in Nitrate Vulnerable Zones.

5.4. Soil compaction: soil properties and yield potential

Schjønning *et al.* (2009) identified soil compaction as the greatest threat to agricultural productivity in Denmark. Other national reports, such as Dobbie *et al.* (2011) have emphasised the importance of soil compaction in developing policies to protect the environment and sustainable food production in the UK. Yield may decrease in compacted soils because of (1) increased mechanical impedance for roots, (2) decreased aeration and (3) decreased water storage in soil (Da Silva and Kay, 1996). These yield reductions can be significant, especially in unirrigated systems (which account for around half of potato land in the UK), with some researchers reporting yield penalties for a variety of crops persisting for up to four years even when compaction was relatively shallow and limited to the plough depth (0-25cm) (Håkansson and Reeder, 1994), with a compacted soil requiring greater fertiliser N applications to achieve comparable yields to those observed from uncompacted areas (Soane and van Ouwerkerk, 1995).

Soil compaction from traffic reduces soil pore space and increases soil bulk densities, and it has been widely recognised for many decades that such effects can decrease potato yield (Blake *et al.*, 1960) and make harvest more difficult (Grant and Epstein, 1973), as well as more recent evidence that soil compaction has long-term impacts in reducing soil biological activity including nitrogen mineralisation rates (Breland & Hansen, 1996; Buliński & Sergiel, 2012) due to its effects in reducing porosity, aeration and associated soil respiration rates (Taghavifar & Mardani, 2014). The tendency for compaction to cause the largest soil pores to be lost has the effect of changing the pore size distribution and hence the water retention characteristic (Dexter, 2004). Hence, soil compaction, especially in subsoil layers, may restrict deep root growth and adversely affect plant access to subsoil water from the middle to late growing season when rainfall is usually sparse and evapotranspiration is high. The resulting increase in drought stress may limit plant growth and yield (Chen & Weil, 2011). Studies conducted by Etana & Håkansson (1994) and Arvidsson (2001) also showed that compaction by heavy machinery – such as that involved in harvesting operations or preparing soil for potato planting - can create compaction down into the subsoil to a depth of at least 0.5m. Such relatively deep soil compaction can lead to long-term yield suppression and such effects can persist for years (e.g. Alakukku & Elonen, 1995; Balbuena *et al.*, 2000). Methods for preparing ground following the previous cereal harvest in a way which helps to remove existing soil compaction and minimise the creation of new compaction during tillage, destoning, ridging and planting activities are therefore of direct benefit to the potato industry, and a focus of this project.

5.5. Cultivations: DTX tine-disc-roller unit – a non-plough option

The Simba Great Plains DTX tool is a tine-disc-roller unit which is capable of operating at a wide range of depths (whereas the Tillerstar operates at a fixed depth). Therefore, the DTX unit has the potential for greater flexibility, depending on the demands of individual sites (such as soil depth and depth to stones or compacted subsoil layers). As equipment such as the DTX does not invert the soil like a plough, it also avoids the risk of bringing wet soil from depth up to the surface, which could make subsequent cultivation activities problematic. Yield data from DTX treatment plots were at least as good as those under conventional ploughing. Harvest 2013 results from the English site show some evidence of greater potato N uptake 9 weeks after emergence under the DTX treatment, and (when a few PCN affected plots are omitted) a slightly (10%) higher potato yield compared to ploughing or Tillerstar treatments, although this effect was not observed in Harvest 2014.

5.6. Cultivations: Tillerstar – a single-pass option

In principle, there is potential value in a single pass tool such as the Tillerstar, which is capable of multiple operations including primary cultivation, ridging and destoning in a single (if very slow) operation. However, the potential attraction of a cultivation system involving a single pass operation (compared to conventional alternatives involving separate operations for cultivation, destoning and bedforming), was not fully realised in this study due to the Tillerstar's very slow operating speed (0.8 km/h) compared to ploughing/DTX (5.2-8.0 km/h) and destoning and ridging activities (2.0-4.4 km/h).

In addition, when considering soil cultivations, timing is of critical importance. In principle, on soils susceptible to soil compaction (e.g. lighter textured, poorly structured arable soils) under moist conditions, one pass by a single very slow and heavy piece of machinery (such as a Tillerstar) may have the potential to cause more structural subsoil damage due to soil compaction than multiple passes with faster, lighter vehicles (Balbuena *et al.*, 2000; Hanza & Anderson, 2005; Buliński & Sergiel, 2012; Taghavifar & Mardani, 2014). This is because, under comparable soil conditions, the first pass with farm machinery traffic over a soil can cause up to 80% of the potential soil compaction i.e. far more than subsequent passes (e.g. Shetron *et al.*, 1988; Bakker & Davis, 1995; Pytka, 2005; Argaw *et al.*, 2013; Daum, 2015). It therefore follows that the concept of combining multiple field operations into a single pass is unlikely to result in lower overall soil compaction – on the contrary, as slower forward velocity means an increased contact time between tyre and soil, this will increase the time of applying downward forces at the same location (Taghavifar & Mardani, 2014) with the effect that slower, heavier machinery can result in compaction reaching greater depths in the subsoil (e.g. Smith and Dickson, 1990) which may be relatively more difficult to rectify later.

Results from this project show that as the Tillerstar includes a destoning function, once stones were deposited this left only around 20cm of available rooting for the potato crop in this treatment - compared to 20-25cm (plough) or 33-40cm (DTX) (see footnotes to Table 2). The Tillerstar thus leaves less soil available for crop rooting, and cannot alleviate soil compaction below 20cm depth which may persist from the previous cereal crop.

Results from the second year (Harvest 2013) of this study including the fully replicated Tillerstar treatment show that leaving this deeper (>20cm depth) subsoil compaction *in situ* results in greater subsoil penetration resistance, and this has the potential to limit potato root development and rooting depth (Figure 3; Table 6). Evidence for this includes the depth to maximum soil compaction being significantly shallower (p<0.01) under the Tillerstar (26cm) compared to other treatments (30-33cm depth), and maximum rooting depths at 9 weeks post-emergence which were only 27cm depth in the Tillerstar treatment but significantly deeper (p<0.001) at 47-53cm depth in DTX and plough treatments (Table 6; Table 8). These findings are corroborated by similar results from the final year's trial in Harvest 2014 (Figure 4; Table 14). Glin´ski & Lipiec (1990) found that decreased root size, retarded root penetration and smaller rooting depth was a common response of root systems to increasing compaction level caused by mechanical impendence and insufficient aeration. Decreased rooting depth and root size can result in greater distances between neighbouring roots and negatively affect both water and nutrient uptake (Tardieu, 1988; Yamaguchi & Tanaka, 1989).

It follows logically, although not tested here, that the observed effects of the Tillerstar treatment on soil properties and rooting may limit the resilience of crops to tolerate intermittently drier conditions, such as those found in unirrigated potato systems. However, this experimental trial was irrigated which may explain why such soil physical effects of cultivation treatment on both compaction and rooting in the fully replicated Tillerstar treatment compared to plough and DTX treatments in Harvest 2013 had no significant impact (p>0.05) on either N uptake 9 weeks post-emergence or yield (Table 7; Table 9).

Indeed, trial results from the Tillerstar treatment show that yields were typically broadly equivalent to those from conventional ploughing, but with hypothetical cost savings associated with a single operation (and the fact that one, not three, pieces of capital equipment need to be obtained and maintained). However, the Tillerstar was evaluated in on light textured, irrigated land with relatively few stones – and was only fully replicated in Harvest 2013. Further work is therefore needed here as it is unclear how this equipment would cope with medium textured soils, or more moderate stone content, or whether the compaction which persists at depth (as the Tillerstar only leaves an available rooting depth of around 20cm) would affect yield on unirrigated potato land where soil moisture (and therefore nutrient supply) may be more limited.

5.7. Cultivations: shallow versus deep de-stoning

The impact of de-stoning depth was evaluated in the replicated trial at both sites in 2013. There was no evidence that shallower destoning had any significant negative effect (p>0.05) on potato rooting, N uptake or tuber yield and quality. Shallower destoning has the potential advantage of reduced draft, reduced fuel use and faster working speeds.

5.8. Cultivations: establishment costs

Because of the relatively small plot sizes in the trials reported in this project, whilst data was collected on working rates and fuel use, it was considered that meaningful assessment of costs of alternative methods for ground preparation prior to planting potatoes were not possible. However, a separate SRUC analysis of the typical costs of alternative methods for ground preparation prior to planting potatoes was carried out in Slingsby in North Yorkshire (Smallwood, 2013). At this site shallow plough, deep plough, Sumo Trio, Shakerator and Tillerstar preparation options were assessed.

Results from that trial showed that overall establishment costs of the different options of ground preparation were remarkably similar at £306-321/ha. Key assumptions in such calculations include vehicle speed, number of passes, fuel use, fuel costs, and labour time/costs.

6. Conclusions

6.1. Cover crops

- There was a demonstrable agronomic benefit of growing cover crops over the winter prior to planting potatoes, by supplying otherwise unavailable N to the potato crop. This was because typically only around 60% of the fertiliser applied to a previous crop of winter cereal is actually taken up by that crop (Defra, 2010). The remainder of the applied fertiliser N remains in the soil post-harvest, and is vulnerable to leaching during the 9 month period before a spring crop, such as potatoes, is established. The potential benefit of growing a cover crop prior to planting potatoes is therefore primarily the saving of valuable soil mineral nitrogen which would otherwise be lost from the soil as rainfall promotes drainage and leaching where land has been left bare or with (dead) stubble over-winter. This study showed that, if managed optimally, cover crops can recover 50-80 kg/ha of this valuable autumn soil mineral nitrogen. There is also an additional benefit from growing cover crops, shown in recent Defra-funded experiments, whereby the good ground cover reduces soil erosion risk and associated loss of fertile topsoil as sediment and phosphorus in surface runoff from shallow and moderately sloping fields (Silgram *et al.*, 2015).
- To be effective, cover crops require establishment as soon as possible after the harvest of the preceding crop (e.g. mid-August in Scotland; mid-August to mid-September in England). Late establishment limits ground cover and N uptake potential, as was found at the Scottish site.
- Cover crop species and seed rate are important factors, and are influenced by local climate and soil conditions. Seed rates of the mustard cover crop were successfully reduced in England between 2012 and 2014 with no effect on cover crop N uptake – and a further more modest reduction in seed rate is plausible to keep net costs down. Results indicate a wide variety of cover crop species are appropriate in much of England including oilseed rape, oil radish, white mustard and winter rye. Mustard is not frost hardy and a winter frost may avoid the need for destruction by flailing. However, in Scotland, the cooler climate means it takes longer to establish good ground cover, and results indicate oilseed rape and white mustard are unsuitable cover crops although oil radish is a viable option.
- Timely destruction of cover crops is critical to promoting their rapid decomposition and release of mineral nitrogen in time to be of use to the next potato crop. Destruction in January or no later than late February is recommended. Delaying destruction after the end of February results in more mature, “woody” cover crops with wider carbon:nitrogen ratios (containing more lignin) which take longer to decompose – which can delay the release of mineral nitrogen beyond the period when it is needed by the following potato crop.
- Cover crops made notable (typically 10-50 kg N/ha) contributions of plant-available N which were recovered by the next potato crop, suggesting the use of cover crops can have agronomic benefit and should be taken into account when considering fertilisation regimes. However there was no significant effect at either site of the use of cover crops on subsequent potato yield, tuber size or quality. Cover crop N uptake is strongly affected by climate and autumn and winter weather conditions. Differences in establishment and ground cover are a function of autumn temperature mainly, although soil moisture is also important. The cooler Scottish

climate required cover crops to be established several weeks earlier than in England (i.e. mid-August rather than early September) in order to achieve good ground cover. Similarly, the cooler Scottish climate may result in slower decomposition of cover crop residues after destruction, which reduces the proportion of the cover crop N which becomes available to the next potato crop (with the remaining N contributing to soil organic matter). The use of cover crops is therefore a much more viable management option on land in central and southern England going into potatoes the following spring.

- Costs of using cover crops before potatoes depend largely on the chosen seed rate and on the seed costs, which vary substantially between cover crop species. Careful species selection based on climate constraints (see above) and cover crop seed price therefore substantially affect the bottom line. Under good growing conditions in England (i.e. a warm, moist winter), there was a small net cost of around £4/ha of growing white mustard as a cover crop. However, this cover crop would have been cost neutral if seed costs or seed rate had been slightly reduced (e.g. by 10-20%).
- There are also other potential agronomic and environmental advantages of growing cover crops (not explicitly investigated in this study) including (i) the possibility to claim "points" or similar for using cover crops under targeted agri-environment schemes; (ii) improvements to soil structure (and associated water holding capacity and available water capacity) and soil organic matter reserves from the cover crop biomass which does not decompose to release mineral N in time to be used by the potato crop; and (iii) reductions of typically 50% in nitrate leaching to local groundwaters from fields when cover crops are grown.
- There was no evidence that the use of cover crops in the winter prior to potatoes affected the presence of slugs associated with the subsequent potato crop.
- There was no evidence that the use of cover crop species such as mustard prior to potatoes had any biofumigation benefits. This was to be expected, as such a crop grown for biofumigation purposes would be grown to maturity, destroyed when temperatures were warmer in the summer, and with residues immediately incorporated into the soil.

6.2. Cultivations

- At both English and Scottish sites, there was no evidence that shallower destoning had any significant negative effect on potato rooting, N uptake, or on tuber yield, size or quality. Shallower destoning has the potential advantages of reduced draft, improved fuel use and faster working speeds.
- At both English and Scottish sites, and in two trials in different years, there was no evidence of any disadvantage of employing non-plough options for preparing ground in the autumn or spring prior to planting potatoes, such as any effect on tuber yield, size or quality. Non-plough options for ground preparation, using equipment such as the Simba Great Plains DTX or Sumo Trio, have the potential practical advantage of greater flexibility across a wider range of operating depths and soil conditions. The DTX for example, can operate down to around 40cm depth (compared to a plough working at 25-30cm depth), but unlike a plough the DTX does not invert the soil but instead uses a disc and tine combination. Consequently, the DTX avoids the risk of bringing wet soil up to the surface from depth (which would occur with a plough), which could pose a risk in autumn and spring as wet soil near the surface can limit trafficability, increase the risk of soil

smearing and compaction, and thereby constrain the timing of subsequent ground preparation activities (such as destoning and bedforming).

- The DTX equipment performed consistently well across sites and years, with its combination of discs and tines offered a viable alternative to conventional inversion tillage using a plough. The potential for this equipment to operate below the conventional plough depth (i.e. down to 35-40cm) means it has the potential to lift and alleviate deeper compaction – such as a plough pan - persisting from the previous cropping. Yields from treatments using the DTX in autumn or spring were at least as good as those using a conventional plough, and at the English site, there was a notably slightly (10%) greater yield from DTX treatment plots compared to either plough or Tillerstar treatment plots.
- The Tillerstar treatment was fully replicated in harvest 2013, but was added as an additional unreplicated area at the funder's request in harvest 2014. Tillerstar results were mixed between sites and years. Overall, in most cases yields appeared to be broadly comparable to those from other cultivation treatments (although when harvested using commercial equipment a considerable quantity of stones were also harvested). However, after stones are deposited, the relatively shallow depth left available for potato rooting (20 cm) compared to plough (20-25cm) and DTX (33-40 cm) options meant that (unlike the DTX) deeper compaction from the previous crop was not alleviated prior to planting. Consequently, there was experimental evidence of significantly greater compaction ($p<0.01$) and shallower rooting depths ($p<0.001$) for potato crops in Tillerstar areas compared to plough and DTX treatment areas. Under different soil conditions (i.e. a drier season and an unirrigated crop), these factors have the potential to adversely affect both tuber yield and quality.
- All three plough and non-plough cultivation options had similar establishment costs. The potential cost saving associated with the single pass nature of the Tillerstar equipment was not realised, as it was negated by its slower operating speed (0.8 km/h compared to 2.0-8.0 km/h) using three separate passes to cultivate, ridge and destone.

6.3. Further work

This study has focused on two sites with light textured soils with a relatively low level of stoniness. These two sites were used to explore the potential advantages and disadvantages of growing cover crops prior to potatoes in two seasons, and the merits of alternative methods for cultivating the ground prior to planting potatoes in two seasons. Further results across a wider range of field sites and growing seasons would be strongly recommended before any broader conclusions are drawn regarding recommendations for potato management across the UK. In addition, the two sites were planted in each year with commercial potato crops which were irrigated as determined by prevailing weather conditions and agronomic need.

Consequently, although conclusions from this research are highly relevant to the industry, they are applicable to a relatively limited range of land growing commercial potatoes and agronomic situations. This research now needs to be extended to broaden the assessments undertaken in this study to include:

(i) **medium textured soils** (silty loams, silty clay loams) used for growing potatoes;

(ii) soils with a **moderate level of stoniness**, which may substantially affect the operational practicalities and efficacy of alternative cultivation equipment;

(iii) **a wider range of weather and seasonal conditions** (which will influence the efficacy and operational practicality of using different cultivation equipment).

(iv) **potato land which is not irrigated** (which will respond differently to cultivation effects on soil properties and potato rooting characteristics / constraints).

(v) **a more rigorous replicated assessment of the single-pass Tillerstar** equipment than was possible in this study, together with other novel new single-pass machinery entering the marketplace, which should test their ability to tolerate wetter operating conditions and more stony soils, and the impact of any shallower rooting depths on yield and tuber quality in unirrigated potato systems.

(vi) an intercomparison of conventional ploughing with **other non-inversion methods, such as the Sumo and Shakerator, and other innovative equipment now being developed by leading manufacturers**.

(vii) an intercomparison of **alternative cover crop species** (beyond the limited selection of the four assessed in this study) and seed rates, to advise the industry how best to minimise costs and maximise operating margin associated with their use. This could include identifying more suitable species which are viable for use in Scotland, possibly in conjunction with undersowing prior to harvesting of the previous crop, in order to ensure better cover crop establishment and resulting efficacy in terms of N supply to the following potato crop.

(viii) The effect of **cover crop destruction method**, as methods which increase the surface area available to soil microorganisms (flailing, maceration etc.) may promote the more rapid release of scavenged N contained in cover crop residues back into plant-available mineral form in time to be of agronomic value to the next potato crop.

Regarding (i) and (ii), compared to the soils considered in this study, more medium textured soils and soils with moderate stoniness will have (a) contrasting responses to traffic in terms of their susceptibility to compaction and smearing; and (b) will respond differently to cultivations aimed at alleviating such compaction by attempting to improve soil hydraulic properties (aeration, porosity, infiltration rate etc.), resulting potato rooting characteristics, and associated water and nutrient supply to the potato crop.

Regarding point (iii), weather conditions can be very variable, and the fact that this study only considered two seasons for cover crops and two seasons for cultivations means that only a narrow range of seasonal weather was considered. Extending this study to cover an additional one or two years is therefore desirable, as this would ensure a wider range of weather conditions and seasons were considered which will ensure advice and recommendations to the industry are applicable to a broader range of prevailing weather conditions (i.e. wet and dry years).

Linked to this, weather conditions become even more important in influencing crop response in potato systems which are not irrigated. In this study, the physical effects of cultivations on bulk density, penetration resistance and potato rooting - which were often statistically significant - did not carry through to final treatment effects on potato yields. This may well be due to the fact that the trials sites were both irrigated. Consequently, the potential constraints on water or nutrient availability – which result from the observed effects of cultivation treatments on soil compaction and/or root development - may have been overcome by the land being irrigated whenever soils began to dry out and approach critical soil moisture deficits. Extending cultivation treatment assessments to **unirrigated** potato land would test in a robust manner whether the physical effects of different cultivation treatments observed in this study can adversely influence potato yield and quality under conditions where both moisture and hence nutrient availability may be limited. The resulting advice on cultivations would be of great interest to the industry, as around half the annual UK potato crop area is not routinely irrigated.

Another machinery manufacturer is currently testing a new machine for ground preparation which provides an alternative one-pass preparation approach to the George Moate Tillerstar but with greater applicability to the wide range of soil conditions that might be experienced in land suitable for potato crops. This machine is being evaluated in the UK (including by SRUC). **The considerable industry interest in single-pass ground preparation options means further assessment of their use and applicability, particularly in relation to soil structure, is now required.**

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8. APPENDIX

Appendix 1. Field diary sheet – key operations

Harvest 2012

Operation	English Site	Scottish Site
Cover crop drilled	21/09/11	24/08/11
Cover crop destroyed by cultivation	24/02/12 *	16/02/12
Plough	21/03/12	16/02/12
Deep ridging	28/03/12	07/05/12
Destoning	28/03/12	07/05/12
Potato planting	29/03/12	07/05/12
Potato harvest	18/09/12	30/10/12

* frost damage evident from 06/02/12

Harvest 2013

Operation	English Site	Scottish Site
Cultivation from stubble: Plough treatments 1 & 2	25/04/13	08/04/13
Cultivation from stubble: DTX treatments 3 & 4	25/04/13	29/04/13
Deep ridging (treatments 1-4)	26/04/13	29/04/13
Destoning (treatments 1-4)	26/04/13	29/04/13
Cultivation from stubble & destoning: Tillerstar (treatment 5)	25/04/13	29/04/13
Potato planting	01/05/13	29/04/13
Potato harvest	01/10/13	08/10/13

Harvest 2014

Operation	English Site	Scottish Site
Cultivation treatments (autumn):	17/09/13	06/09/13 Treatments 2 & 4 (DTX)
Cover crop drilled	17/09/13	02/08/13 (Treatment 3) 06/09/13 (Treatment 4)
Cover crop destroyed	18/03/14	31/03/14
Cultivation treatments (spring): Treatments 1-4 (Plough)	04/04/14	31/03/14
Cultivation treatment (spring): Treatment 5 (DTX)	04/04/14	16/04/14
Deep ridging	04/04/14	28/04/14
Destoning	05/04/14	28/04/14
Tillerstar (1 plot)	10/04/14	28/04/14
Potato planting	05/04/14	28/04/14
Potato harvest	15/09/14	15/10/14

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