NIAB TAG

The STAR Project
(Sustainability Trial in Arable Rotations)

Long-term report
Years 1-10 (2006 – 2015)

A report for the The Felix Thornley Cobbold Agricultural Trust

NIAB TAG
This project was delivered through NIAB TAG in accordance with the agreed protocol and associated Standard Operating Procedures. The results presented fully and accurately reflect our interpretation of the data generated.

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1. Summary

The STAR project (Sustainability Trial in Arable Rotations) is a long-term study at Stanaway Farm, Otley, Suffolk on a Beccles/Hanslope Series (heavy) clay soil. Research is delivered through NIAB TAG, supported in part by The Felix Thornley Cobbold Trust (and historically the Chadacre Agricultural Trust) and guided by an independent steering group. Four different methods of cultivation and four different types of rotation are used within the STAR project. This forms a fully factorial design with 16 treatments. All rotations grow wheat every other year, the year between is a break crop/fallow year. Winter cropping has a winter sown break crop, spring cropping a spring sown break crop, continuous wheat grows wheat every year and the alternate fallow grows wheat every other year (alternating with a cover crop fallow). Cultivation approaches follow an annual plough approach, a shallow (c. 10 cm) or deep (c. 20 cm) non-inversion approach or a managed system (decided annually determined by field assessment).

Findings demonstrate clear impacts of rotation and cultivation on agronomy and production, including (but not limited to) weed burden, soil condition and mycotoxin risks. With regard to yields, differences between cultivation systems have been small, however, the highest yields, considered over all crops, have been associated with plough based systems. With regard to rotational gross margins, the winter cropping systems have resulted in highest margins, often with lower variability compared to other approaches. Considering cultivation approach, differences in gross margin have been smaller than those observed for rotation, and differences between systems are small (probably smaller than initially envisaged at the project outset). Of the cultivation systems, the managed approach has performed well (that is making an informed annual cultivation decision, based on crop, soil and agronomic considerations). However, of the consistent systems (i.e. where the same approach is used every season), the deep non-inversion tillage has performed well with similar yields and margins to the managed approach. Findings for wheat demonstrate much less impact of tillage on yield, with (of the consistent approaches) deep non-inversion systems resulting in the highest margins.

STAR continues to deliver new information (e.g. as further crop sequences build in the rotation wider cross season analysis and comparisons are possible) and provides an outstanding future research platform (e.g. for soil biology). Currently a number of farmer and student facing events are held on the site each year and a range of research projects and groups use the facility. Going forward, this contemporary fully replicated and well quantified site continues to deliver a comparison of arable system approaches, using farm scale equipment and techniques; providing a powerful and unique research, education and knowledge exchange combination.

Ten things we've learned from STAR:

1. STAR system and rotation choices have had an agronomic impact on factors including mycotoxin risks and weed burden (notably bromes in non-inversion wheat systems).
2. Shallow non-inversion tillage is leading to progressively tighter soils in the continuous wheat rotation and across the winter and spring cropping rotations.
3. Considering yields over all crops in the rotation, the difference between cultivation systems is small, however, of the consistent systems, ploughing is tending to give the highest yields.
4. While ploughing might give high yields, of the consistent cultivation systems across seasons, the highest margins have been associated with the deep non-inversion system: although again differences are relatively small.
5. A variable managed approach (an informed decision each season based on soil, season and agronomic drivers), has performed similarly to the deep non-inversion system.
6. Considering wheat alone across seasons, for the consistent cultivation systems, there is little yield difference, with deep non-inversion systems resulting in the highest margins.
7. Findings perhaps suggest that tillage decisions are more critical in break crops and also highlight the value of informed soil management decisions to maximise performance.
8. Cumulatively, STAR rotational choices have tended to have a bigger impact on margin than primary tillage decisions; with winter cropping rotations giving the higher margins.
9. Consideration of timeliness and speed of working across the farm, as well as yield and margin, is critical when scaling findings from STAR up to a farm level.
10. One key finding is how much we owe to the supporting Trusts, the STAR advisory group and notably our site host John Taylor; without their input this project would not happen.

2. Acknowledgments

The STAR project is delivered through NIAB TAG, supported in part by The Felix Thornley Cobbold Trust and historically by the Chadacre Agricultural Trust. In recent seasons some support has also been delivered through external projects making use of the platform; for example the AHDB-Cereal and Oilseed Project RD 2012-3786 (To test and demonstrate sustainable soil management: integration of major UK field experiments) and other projects. The research has also benefitted from an independent steering committee. This includes local farmers and consultants; thanks and acknowledgment are extended to John Taylor (our host farmer) and other members of this group.

3. Aim and Objectives

Aim
To examine different cultivation systems for sustainable arable production.

Objectives
- To examine different rotation systems and to explore how they interact with cultivation systems and required inputs.
- To demonstrate to Suffolk farmers on Beccles/Hanslope series clay soil alternative systems of cultivation across the rotation.

4. Methods

In autumn 2005 a field experiment was set up at Stanaway Farm, Otley (Suffolk), supported by the Felix Thornley Cobbold Trust to study different cultivation techniques within a series of arable rotations; this research project was termed the STAR project (Sustainability Trial in Arable Rotations). The experiment was established in Nelson Field (Otley, Suffolk), on a heavy Beccles/Hanslope clay soil (which is representative of many farms in the region). The large (36m x 36m) plot system ensures that modern techniques and farm scale equipment can be utilised to reflect local farm practice, unlike many previous experiments. The experiment is a fully replicated factorial design with three replicates. Permanent grass pathways on the site allow each plot to be accessed independently. In each plot the outside area is treated as a 'headland' and all assessments and samples are taken from the central plot areas. Dedicated sacrifice areas are also designated in each plot for destructive sampling; these areas are not used for yield assessment. Each treatment is managed in accordance with the specific requirements of that approach and all inputs are consistent with local best practice. Crop and yields are recorded each season with a Sampo plot combine.

Four different methods of cultivation and four different types of rotation are used within the research project; giving a fully factorial design delivering 16 treatments (Table 1). All rotations grow wheat every other year, the year between is a break crop/fallow year. Winter cropping has a winter sown break crop, spring cropping a spring sown break crop, continuous wheat grows wheat every year and the alternate fallow grows wheat one year and is left fallow (with cover crop treatment) the next. Cultivation approaches follow an annual plough approach, a shallow (c. 10cm) or deep (c. 20-25cm) non-inversion approach (typically using tine and disc based systems) or a managed system decided on an annual basis (this is an informed decision made each season based on soil, season and agronomic drivers). Margin data are based on a gross output minus direct input and machinery costs for prices relevant to each production season; all crop prices and input costs are determined annually through market bulletin publications and in agreement with the advisory committee. Additional costs associated with the fallow delivery have not been included, but would have typically been c. £120-140/ha each season.

Table 1: Summary of STAR project rotation and cultivation treatments.

	Rotation	Cropping									
		2006 (Yr 1)	**2007 (Yr 2)**	**2008 (Yr 3)**	**2009 (Yr 4)**	**2010 (Yr 5)**	**2011 (Yr 6)**	**2012 (Yr 7)**	**2013 (Yr 8)**	**2014 (Yr 9)**	**2015 (Yr 10)**
1	Winter cropping	wosr	ww	wbn	ww	wosr	ww	wbns	ww	wosr	ww
2	Spring cropping	sbn	ww	soats	ww	sbn	ww	sln	ww	soats	ww
3	Continuous wheat	ww	ww	ww	ww	ww	ww	ww	ww	ww	ww
4	Alternate fallow	fal	ww	fal	ww	fal	ww	fal	ww	fal	ww

Cropping key – ww (winter wheat), wosr (winter oilseed rape), soats (spring oats), sbn (spring bean), wbn (winter bean), sln (spring linseed), fal (fallow).

	Cultivation	
1	Annual plough	Treatment is ploughed every year (inversion to 20-25cm).
2	Managed approach	Decision on cultivation regime is not decided until much nearer the time, decision is based around soil/weather conditions, previous cropping, weed burden, soil assessments etc.
3	Shallow tillage	Treatment is cultivated to ≈10cm using a non-inversion technique.
4	Deep tillage	Treatment is cultivated to ≈20-25cm using a non-inversion technique.

5. Seasonal summaries

The following sections set out a summary of the annual reports from seasons 1 to 10. The text is based on that presented in the individual seasonal update reports. Additional further seasonal details are also presented in the Appendix.

5.1 Year 1 (2006) Summary

Oilseed rape plots *cv*. Astrid, established well from both drilled and broadcast plots (Table 2), with little difference seen between the different cultivation depths for the deep / shallow tillage systems. Ploughed plots however had a much higher plant population of c. 95 plants/m², where as the other treatments had an average of 45-68 plants/m² (Table 3). Through the growing season the treatments with fewer plants appeared more vigorous and from inspection of the roots at the beginning of stem extension plants in the ploughed treatment appeared to have poorer root systems. Final yields in the oilseed rape were highest where the plough was used as the establishment technique (Table 4). Oil contents were measured, but showed no significant differences. Yield figures were then used to give a 'gross margin minus machinery cost': this indicated that all treatments were similar. Continuous wheat plots were established at the beginning of October (*cv*. Xi19), into good seedbeds and establishment was good. Latitude (silthiofam) treated seed was used as this wheat was a 3rd wheat. Plant counts indicated that the ploughed treatments (annual plough and managed approach) had more plants/m², but not significantly more than the non-inversion treatments. The non-inversion wheat plots showed signs through the winter of being starved of nitrogen (yellower in colour), but a soil mineral N test in February showed that there were no differences in available N. Final yields in the wheat again favoured the plough, but this was not significant. Both deep and shallow tillage treatments yielded 0.5t/ha less than the managed approach and annual plough treatments. Margin figures demonstrated that the biggest margins were made using the shallow tillage method in this season. Spring beans were established in early February *cv*. Quattro into good conditions. A Claydon drill was used to plant the beans into the non-inversion treatments; it was then also used in the ploughed plots, although this machine was not as essential in these plots as it was as the non-inversion tillage treatments. All treatments were drilled at a depth of 10cm. Establishment was

Ploughed treatment oilseed rape roots (left) versus broadcast treatment (right)

good, but rook damage was most severe in the shallow tillage treatment where the bean seeds were easiest to find. Final plant counts did show fewer plants in the shallow tillage treatment. Further plant losses occurred in the late growing season in this treatment due to fusarium root rot; probably due to poor surface drainage. Final yields in the spring beans showed a distinct advantage to autumn ploughing in preparation for spring sowing. While the deep tillage treatment yielded significantly less than the ploughed treatments this was still an improvement over the shallow treatment (where no autumn work was carried out at all). Margin figures were highest for the ploughed treatments. The alternate fallow treatments remained as stubble, which greened up in the spring with a mixture of volunteers, black-grass, oats, brome, annual meadow grass and broad leaved weeds. This was sprayed with glyphosate in May before viable grass weed seeds were set. A mustard cover crop was then sown straight into the stubble; this was left to grow until the cultivations were carried out for year two in July.

Table 2. Field details for year 1 (2005/2006).

Trial Id	**OT06-600**	
Cropping	Winter cropping	Winter oilseed rape (*cv.* Astrid)
	Spring cropping	Spring beans (*cv.* Quattro)
	Continuous wheat	Winter wheat (*cv.* Xi19)
	Alternate fallow/wheat	Cover crop fallow (mustard)
Cultivations	Shallow tillage	Sub-cast (Sept 05); Claydon Drill (Feb 06) or Sumo Trio (Sept 05), working with legs raised and discs (10 cm).
	Deep tillage	Sub-cast (Sept 05) or Flatlift and Press (Sept 05)
	Managed approach	See Appendix A
	Annual plough	Ploughed (Sept 05)

Table 3. Plant population and ear count summary information from STAR year 1 (2005/2006).

	Plants/m^2 (Assessed on 21/02/06 and 20/06/06)			
Tillage	Winter (OSR)	Spring (Beans)	Cont (WW)	Alt Fallow
Plough	96	39	184	-
Managed	68	31	203	-
Shallow	45	19	172	-
Deep	46	30	167	-
Average	64	30	182	-
LSD	-	7.7	20.5	
CV %	-	17.4	11.6	

Table 4. Yield and margin summary information from STAR year 1 (2005/2006).

	Yield (t/ha)					**Gross margin – machinery cost (£/ha)**			
	Winter (OSR)	Spring (Beans)	Cont (WW)	Alt Fallow		Winter (OSR)	Spring (Beans)	Cont (WW)	Alt Fallow
Plough	4.4	3.9	8.9	-		279	124	305	-
Managed	4.0	3.8	9.1	-		298	114	322	-
Shallow	3.8	2.4	8.4	-		273	46	341	-
Deep	3.9	3.3	8.4	-		269	73	306	-
Average	4.0	3.4	8.7	-		280	89	319	-
LSD	0.34	7.69	0.5						
CV %	3.0	17.4	3.3						

Margins based on wheat at £85/t, OSR at £160/t and beans at £92/t.

5.2 Year 2 (2007) Summary

During year 2 the entire STAR project was in winter wheat (*cv*. Einstein) that was drilled into good conditions on September 15th and received a following roll (Table 5). Plant counts carried out in November showed no significant differences between treatments (Table 6). Growth characteristics throughout the winter were similar, with the ploughed treatment looking more even. A winter vigour score also showed no significant differences. Assessments made during the growing season showed no significant difference to eyespot between the treatments. There was a slight difference in lodging assessments, where the annual plough plot lodged less than the other non-inversion plots, although the highest amount of lodging was 9.3% of the plot lodged.

Final yields showed an advantage to the plough and the deep tillage treatment which were significantly higher than the shallow tillage and managed approach. Yield data was used to calculate gross margins and the cost of the machinery inputs were then subtracted to provide 'gross margin minus machinery cost' information; findings are shown in Table 7. Significant differences in mycotoxin levels with respect to rotation and cultivation were also detected in years 2: further details of these findings are presented in section 6.2.

Table 5. Field details for year 2 (2006/2007).

Trial Id	**OT07-600**	
Cropping	All rotations	*Winter wheat (cv. Einstein)*
Cultivations	Shallow tillage	Sumo Trio (Sept 06), working with legs raised and discs (10 cm).
	Deep tillage	Sumo Trio (Sept 06), working with discs and deeper legs (20 cm)
	Managed approach	See Appendix A
	Annual plough	Ploughed and pressed (Sept 06)

Table 6. Plant population and ear count summary information from STAR year 2 (2006/2007).

	Plants/m2 (Assessed on 10/11/06)				
Tillage	Winter	Spring	Cont	Alt Fallow	Average
Plough	180	153	190	179	176
Managed	166	152	188	168	169
Shallow	143	156	140	180	155
Deep	155	181	174	179	172
Average	161	161	173	177	
LSD	40.7				
CV %	14.6				

Table 7. Yield and margin summary information from STAR year 2 (2006/2007).

	Yield (t/ha)						**Gross margin – machinery cost (£/ha)**			
	Winter	Spring	Cont	Alt Fallow	Average		Winter	Spring	Cont	Alt Fallow
Plough	9.45	10.03	5.77	9.32	8.64		742	843	266	729
Managed	8.27	9.54	6.13	8.27	8.05		639	811	304	635
Shallow	8.20	8.77	4.50	8.60	7.52		627	728	134	676
Deep	9.27	9.00	4.75	8.10	7.78		760	749	155	610
Average	8.80	9.34	5.29	8.57			692	783	215	663
LSD	0.97									
CV %	7.2									

Margins based on wheat at £125/t

5.3 Year 3 (2008) Summary

Cropping this year was continuous wheat, winter beans (winter cropping rotation), spring oats (spring cropping rotation) and fallow with mustard drilled in April (Table 8). Establishment technique did not significantly affect plant populations (Table 9), except for the shallow cultivated winter beans that failed due to poor emergence and rook damage. Tillage techniques did not influence fertile tiller populations (wheat and oats) or take-all index and foliar disease development (wheat). Grass weed levels were higher in the continuous wheat non inversion plots compared with the spring cropped plots. Meadow brome levels were highest where the crop had been continually established using shallow tillage methods throughout the project (three years). Brome heads in the deep tillage plots were higher compared with the managed approached, which was also deep tilled, but the managed approach plots had been ploughed in the previous two years. No grass weed heads of any species were observed in the ploughed plots. In this season winter beans established by annual ploughing followed by drilling with a Claydon drill produced the highest yield (6.07 t/ha) and gross margin over machinery costs; data presented for the shallow drilled beans should be treated with caution (and have been disregarded for ongoing analysis) as pest damage (rooks) influenced plot establishment and areas were re-sown at a later date (this was a trial artefact rather than treatment effect) (Table 10). For spring oats deep tillage (Sumo at 20 cm) produced the best yield (3.68 t/ha) and margin. For continuous wheat shallow tillage (Sumo disced to 10 cm) produced the highest yield (7.91 t/ha) and margin. Overall the highest margins were achieved by winter beans established using a plough and Claydon drill (£568/ha based on a seed price of £160/t).

Table 8. Field details for year 3 (2007/2008).

Trial Id	**OT08-600**	
Cropping	Winter cropping	Winter beans (*cv*. Wizard)
	Spring cropping	Spring oats (*cv.* Bullion)
	Continuous wheat	Winter wheat (*cv.* Brompton)
	Alternate fallow/wheat	Cover crop fallow (mustard)
Cultivations	Shallow tillage	Claydon Drill (Sept 07) or Sumo Trio (Sept 07), working with legs raised and discs (10 cm).
	Deep tillage	Sumo Trio (Sept 07), working with discs and deeper legs (20 cm)
	Managed approach	See Appendix A
	Annual plough	Ploughed and pressed (Sept 07)

Table 9. Plant population and ear count summary information from STAR year 3 (2007/2008).

	Plants/m² **(Assessed on 14/02/08)**				**Ears/m²** **(Assessed on 01/07/08)**			
	Winter (beans)	Spring (oats)	Cont (WW)	Alt Fallow	Winter (beans)	Spring (oats)	Cont (WW)	Alt Fallow
Plough	22	-	155	-	-	411	333	-
Managed	18	-	126	-	-	393	318	-
Shallow	*	-	143	-	-	379	328	-
Deep	17	-	159	-	-	335	302	-
Average	*19*		*194*			*380*	*320*	
LSD	*7.7*	-	*29.4*	-	-	*59.3*	*31.0*	-
CV %	*17.9*	-	*10.1*	-	-	*7.8*	*4.8*	-

**Crop establishment was poor due to tilth issues and the crop was re-drilled with spring beans.*

Table 10. Yield and margin summary information from STAR year 3 (2007/2008).

	Yield (t/ha)				Gross margin – machinery cost (£/ha)			
	Winter (beans)	Spring (oats)	Cont (WW)	Alt Fallow	Winter (beans)	Spring (oats)	Cont (WW)	Alt Fallow
Plough	6.07	3.32	7.02	-	568	186	168	-
Managed	5.53	3.34	7.41	-	510	186	233	-
Shallow	(1.33)	3.33	7.91	-	-	217	302	-
Deep	5.29	3.68	6.95	-	489	255	183	-
Average	5.56	3.42	7.32	-	522	211	222	-
LSD	2.91	0.57	1.49					
CV %	22.8	8.5	10.2					

Margins based on wheat at £110/t, oats at £150/t and beans at £160/t.

5.4 Year 4 (2009) Summary

During year 4 (2008/09) the entire STAR project was in winter wheat (*cv*. Oakley) and establishment techniques remained as described in section 4. The wet conditions in autumn 2008 resulted in a drilling date of 02/10/08 (Table 11). Over-winter soil assessments taken during the 2008/09 season suggest that soils subject to continued shallow cultivation have poorer surface structure and over winter drainage (*cf.* other cultivation techniques). It is thought that wet weather over the last two seasons has contributed to this effect. The drier summer in 2009, where soil surface cracking was apparent, may have impacted on this subsequent to assessment. These effects of sustained shallow cultivation have also started to become apparent in an analogous research project being carried out on a lighter soil type at NIAB TAG Morley (the New Farming Systems (NFS) project). Plant population details are presented in Table 12. Grass-weed build up has also become readily apparent in the non-inversion continuous wheat treatments since the initiation of the STAR project; with between 22 and 45 meadow brome heads/m^2 recorded in 2009. When the project started a range of grass species were present in the field but they were not at levels that would be considered of agronomic concern. With respect to yield and financial data from 2008/09; highest yields with respect to rotation tended to be with winter cropping (10.39 t/ha) and the lowest with continuous wheat (5.32 t/ha) (Table 13). Regarding cultivation, highest yields were associated with deep non-inversion treatments (9.00 t/ha). The highest individual treatment yield (10.82 t/ha) was associated with 'deep cultivation, winter cropping'. Margins (calculated as gross output minus input costs and direct machinery costs) tended to reflect yield data. Mycotoxin analysis was also carried out on grain samples; while DON (deoxynivalenol) levels were low, non-inversion tillage generally resulted in higher levels than inversion systems.

Table 11. Field details for year 4 (2008/2009).

Trial Id	**OT09-197**	
Cropping	All rotations	Winter wheat (*cv*. Oakley)
Cultivations	Shallow tillage	Sumo Trio (22/09/08), working with legs raised and discs (10 cm).
	Deep tillage	Sumo Trio (22/09/08), working with discs and deeper legs (20 cm)
	Managed approach	See Appendix A
	Annual plough	Ploughed (22/09/08) followed by culti-press on the 30/09/08.
Sowing date	All rotations	02/10/08

Table 12. Plant population and ear count summary information from STAR year 4 (2008/2009).

	Plants/m² (Assessed on 18/03/09)						Ears/m² (Assessed on 19/06/09)				
Tillage	Winter	Spring	Cont	Alt Fallow	Average		Winter	Spring	Cont	Alt Fallow	Average
Plough	278	267	285	268	275		334	307	281	323	311
Managed	267	293	288	300	287		351	329	302	334	329
Shallow	307	288	293	303	298		327	346	261	344	320
Deep	328	263	330	298	305		350	336	253	329	317
Average	295	278	299	292			341	329	274	333	
LSD	40.5						46.7				
CV %	8.4						8.8				

Table 13. Yield and margin summary information from STAR year 4 (2008/2009).

	Yield (t/ha)						Gross margin – machinery cost (£/ha)			
	Winter	Spring	Cont	Alt Fallow	Average		Winter	Spring	Cont	Alt Fallow
Plough	10.07	8.81	4.63	10.51	8.51		388	220	-184	442
Managed	10.44	9.13	6.10	9.66	8.83		465	273	-37	357
Shallow	10.22	9.69	5.43	9.85	8.80		454	359	-53	427
Deep	10.82	9.55	5.11	10.50	9.00		503	334	-96	481
Average	10.39	9.30	5.32	10.13			453	297	-93	427
LSD	0.85									
CV %	5.7									

Margins based on diesel at 55p/l, nitrogen at 90p/kg and wheat at £100/t.

5.5 Year 5 (2010) Summary

During year 5 (2009/10) cropping was in the break cropping year (Table 14). Soil penetration data has been collected across the project and differences between systems are becoming increasingly apparent, for example, there is evidence that the alternate wheat fallow continues to show increasing soil strength in shallow tillage. Grass weed build up has also become problematic in the non-inversion continuous wheat treatments, and despite increases in herbicide inputs (and associated costs) there were clear effects in terms of reduced yield and margin performance compared to plough tillage. Crop population data are presented in Table 15. In year 5 the highest crop yields were achieved using plough tillage in the continuous winter wheat (8.2 t/ha) and the spring beans (2.7 t/ha) while the 'sub-cast' technique produced the highest oilseed rape yield (3.6 t/ha) (Table 16). Margins (calculated as gross output minus input costs and direct machinery costs) tended to reflect yield data. Cultivation system choices demonstrated little difference between plough and deep tillage; however, deep tillage treatments would have resulted in higher work-rates (*cf*. ploughing). To date shallow cultivation practices have resulted in margins somewhat less than other approaches. The 'managed approach' continues to achieve the highest cumulative margin compared to all other approaches and suggests improved system performance where cultivation decisions are guided by field conditions at the time of cultivation and past soil assessments.

Table 14. Field details for year 5 (2009/2010).

Trial Id	**OT10-197**	
Cropping	Winter cropping	Winter oilseed rape (*cv.* DK-Cabernet)
	Spring cropping	Spring beans (*cv.* Fuego)
	Continuous wheat	Winter wheat (*cv.* Oakley)
	Alternate fallow/wheat	Cover crop fallow (mustard)
Cultivations	Shallow tillage	Sumo Trio (Late August/Early Sept), working with legs raised and discs (10 cm).
	Deep tillage	Sumo Trio (Late August/Early Sept), working with discs and deeper legs (20 cm)

	Managed approach	See Appendix A
	Annual plough	Plough and pressed (Late August/Early Sept)

Table 15. Plant population and ear count summary information from STAR year 5 (2009/2010).

	Plants/m² **(Assessed on 29/10/09 and 26/11/09)**				**Ears/m²** **(Assessed on 18/06/10)**			
	Winter (OSR)	Spring (beans)	Cont (WW)	Alt Fallow	Winter (OSR)	Spring (beans)	Cont (WW)	Alt Fallow
Plough	106	-	219	-	-	-	448	-
Managed	50	-	224	-	-	-	485	-
Shallow	128	-	196	-	-	-	426	-
Deep	51	-	208	-	-	-	449	-
Average	84		212				452	
LSD	16.6	-	31.0	-	-	-	64.9	-
CV %	9.9	-	7.3	-	-	-	7.2	-

Table 16. Yield and margin summary information from STAR year 5 (2009/2010).

	Yield (t/ha)				**Gross margin – machinery cost (£/ha)**			
	Winter (OSR)	Spring (beans)	Cont (WW)	Alt Fallow	Winter (OSR)	Spring (beans)	Cont (WW)	Alt Fallow
Plough	3.47	2.70	8.21	-	552	182	623	-
Managed	3.61	2.63	8.29	-	629	170	634	-
Shallow	3.35	2.17	6.88	-	598	100	409	-
Deep	3.55	2.13	6.96	-	611	118	410	-
Average	3.50	2.41	7.59		598	143	519	-
LSD	0.47	0.53	0.92					
CV %	6.8	11.0	6.1					

Margins based on diesel at 55ppl; nitrogen at 65p/kg N and wheat at £130/t; Oilseed rape at £280/t and beans at £140/t.

5.6 Year 6 (2011) Summary

In year 6 (2010/11) the entire experiment was in winter wheat (*cv.* Oakley) (Table 17). The abnormally dry weather during the spring proved challenging; with some impact on plant populations (Table 18). Soil penetration data has been collected across the project and differences between systems are evident: for example, findings suggest that the shallow tillage continues to show increasing soil strength and there is a suggestion that for plough tillage a plough pan is forming at about 20 cm, with an appreciable increase in soil strength thereafter. Grass weed control across rotational or cultivation approaches has not been problematic except in the non-inversion continuous wheat treatments, that resulted in a greater density of grass weeds present compared to plough tillage; despite increases in herbicide inputs (and associated costs). In year 6 the highest crop yields were achieved in the spring cropping rotation (7.6 t/ha) (Table 19). Margins (calculated as gross output minus input costs and direct machinery costs) tended to reflect yield data. Cultivation system choices demonstrated very little difference between plough and deep tillage; however, deep tillage treatments would have resulted in higher work-rates compared to ploughing.

Table 17. Field details for year 6 (2010/2011).

Trial Id	**OT11-197**	
Cropping	All rotations	Winter wheat (*cv*. Oakley)
Cultivations	Shallow tillage	Sumo Trio (13/09/10), working with legs raised and discs (10 cm).
	Deep tillage	Sumo Trio (13/09/10), working with discs and deeper legs (20 cm).
	Managed approach	See Appendix A

	Annual plough	Ploughed and pressed (06/09/10).

Table 18. Plant population and ear count summary information from STAR year 6 (2010/2011).

	Plants/m² **(Assessed on 11/02/11)**						**Ears/m²** **(Assessed on 28/06/11)**				
Tillage	Winter	Spring	Cont	Alt Fallow	Average		Winter	Spring	Cont	Alt Fallow	Average
Plough	228	184	178	211	200		319	314	299	304	309
Managed	176	193	120	210	175		313	326	238	333	303
Shallow	173	218	163	203	189		323	337	264	319	311
Deep	196	211	143	217	192		317	347	309	326	325
Average	193	202	151	210			318	331	278	321	
LSD	37.2						45.3				
CV %	11.8						8.7				

Table 19. Yield and margin summary information from STAR year 6 (2010/2011).

	Yield (t/ha)						**Gross margin – machinery cost (£/ha)**			
	Winter	Spring	Cont	Alt Fallow	Average		Winter	Spring	Cont	Alt Fallow
Plough	7.33	7.40	5.67	6.93	6.83		526	536	201	466
Managed	6.91	7.57	6.37	6.47	6.83		496	595	327	418
Shallow	6.85	7.83	7.44	7.15	7.32		487	634	500	532
Deep	7.65	7.95	6.63	7.35	7.40		595	640	366	550
Average	7.19	7.69	6.53	6.98			526	601	349	492
LSD t/ha	0.978									
CV %	8.3									

Margins based on diesel at 65p/l, nitrogen at 75p/kg N and wheat at £150/t.

5.7 Year 7 (2012) Summary

Year 7 (2011/12) was a break cropping year (Table 20). The cold and wet weather during the spring proved challenging, particularly for establishing the spring sown linseed (Table 21) and yield data from the linseed treatments should be considered in the context of the season. Soil penetration data comparing cultivation approaches in the continuous wheat and winter cropping rotations indicated that the shallow cultivation resulted in tighter soils compared to the plough, deep tillage or managed approach. In year 7 the highest crop yields were achieved using a 'managed' approach in the continuous winter wheat (9.2 t/ha) and the spring linseed (2.3 t/ha), while the deep tillage produced the highest bean yield (5.1 t/ha) (Table 22). Margins (calculated as gross output minus input costs and direct machinery costs) tended to reflect yield data.

Table 20. Field details for year 7 (2011-2012).

Trial Id	**WW12-002**	
Cropping	Winter cropping	Winter beans (*cv*. Wizard)
	Spring cropping	Spring Linseed (*cv*. Altess)
	Continuous wheat	Winter wheat (*cv*. Santiago)
	Alternate fallow/wheat	Cover crop fallow (mustard)
Cultivations	Shallow tillage	Sumo Trio (09/09/11), working with legs raised and discs (10 cm).
	Deep tillage	Sumo Trio (09/09/11), working with discs and deeper legs (20 cm).
	Managed approach	See Appendix A
	Annual plough	Ploughed and pressed (06/09/2011)

Table 21. Plant population and ear count summary information from STAR year 7 (2011/2012).

	Plants/m^2 (Assessed on 16/03/12 and 19/05/12)				Ears/m^2 (Assessed on 29/06/12)			
	Winter (Beans)	Spring (Linseed)	Cont (WW)	Alt Fallow	Winter (Beans)	Spring (Linseed)	Cont (WW)	Alt Fallow
Plough	21	143	169	-	-	-	304	-
Managed	22	187	215	-	-	-	310	-
Shallow	22	150	241	-	-	-	296	-
Deep	17	169	215	-	-	-	311	-
Average	21	162	210				305	
LSD	9.8	66.4	53.1	-	-	-	29.1	-
CV %	24.3	20.5	12.6	-	-	-	4.8	-

Table 22. Yield and margin summary information from STAR year 7 (2011/2012).

	Yield (t/ha)				Gross margin – machinery cost (£/ha)			
	Winter (Beans)	Spring (Linseed)	Cont (WW)	Alt Fallow	Winter (Beans)	Spring (Linseed)	Cont (WW)	Alt Fallow
Plough	4.60	1.72	9.11	-	836	178	966	-
Managed	4.69	2.27	9.18	-	850	392	1024	-
Shallow	4.52	1.46	8.98	-	852	122	1002	-
Deep	5.14	1.86	8.97	-	1010	249	987	-
Average	4.75	1.83	9.06	-	887	235	995	-
LSD t/ha	0.85	1.17	1.11	-				
CV %	8.9	28.3	6.2	-				

Margins based on diesel, 68ppl; nitrogen, 85p/kg N; wheat, £175/t; linseed £350/t; beans, £275/t.

5.8 Year 8 (2013) Summary

In 2012/13, STAR project year 8, the experiment was in winter wheat (*cv.* Santiago) (Table 23). Cultivation systems remain as described in section 4, although due to very wet autumn conditions the study was drilled in two tranches due to poor field conditions. The abnormally wet weather during the autumn proved challenging and is believed to have resulted in the poor performance of the non-inversion systems in the continuous wheat rotation (Table 24). Soil penetration data collected and compared across cultivation approaches, irrespective of rotation, indicated that the shallow cultivation resulted in tighter soils compared to the plough tillage, and to a lesser extent, deep tillage or managed approach in 2012/13. In year 8 the highest crop yields were achieved using 'managed' approach in the spring rotation (9.50 t/ha) and the lowest crop yields resulted from the 'shallow non-inversion' continuous wheat rotation (5.85 t/ha) (Table 25). Margins (calculated as gross output minus input costs and direct machinery costs) tended to reflect yield data.

Table 23. Field details for year 8 (2012/2013).

Trial Id	**OT13-002**	
Cropping	All rotations	Winter wheat (*cv*. Santiago)
Cultivations	Shallow tillage	Sumo Trio (31/08/12), working with legs raised and discs (10 cm).
	Deep tillage	Sumo Trio (31/08/12), working with discs and deeper legs (20 cm).
	Managed approach	See Appendix A
	Annual plough	Ploughed and pressed (04/09/12).

Table 24. Plant population and ear count summary information from STAR year 8 (2012/2013).

	Plants/m² **(Assessed on 18/12/12)**						**Ears/m²** **(Assessed on 05/07/13)**				
Tillage	Winter	Spring	Cont	Alt Fallow	Average		Winter	Spring	Cont	Alt Fallow	Average
Plough	114	123	110	116	116		366	352	298	336	338
Managed	124	126	103	106	115		412	366	307	349	359
Shallow	81	114	67	126	97		354	366	187	312	305
Deep	122	130	72	143	117		344	362	294	357	339
Average	110	123	88	123			369	362	272	339	
LSD	30.4						48.7				
CV %	16.4						8.7				

Table 25. Yield and margin summary information from STAR year 8 (2012/2013.

	Yield (t/ha)						**Gross margin – machinery cost (£/ha)**			
	Winter	Spring	Cont	Alt Fallow	Average		Winter	Spring	Cont	Alt Fallow
Plough	9.39	9.04	7.08	8.91	8.61		768	716	422	696
Managed	8.92	9.50	7.84	8.23	8.62		743	830	581	652
Shallow	8.62	8.92	5.85	8.65	8.01		711	756	295	715
Deep	8.66	9.16	6.48	8.91	8.30		704	779	377	741
Average	8.90	9.16	6.81	8.68			732	770	419	701
LSD	1.14									
CV %	8.2									

Margins based on diesel at 68ppl; nitrogen at 80p/kg N and wheat at £150/t.

5.9 Year 9 (2014) Summary

For year 9 (2013/14) the experiment returned to break crops, other than the continuous wheat, (Table 26) and crop population level were generally good (Table 27). The higher levels of sunshine duration during June and July are likely to have contributed to some of the highest continuous wheat grain yields recorded within the project to date (Table 28). Soil penetration data for cultivation approaches, irrespective of rotation, indicates that the shallow cultivation continued to result in tighter soils compared to the plough tillage, and to a lesser extent, deep tillage or managed approach in 2013/14. In year 9 the highest crop yields were generally associated with plough tillage. However, margins (calculated as gross output minus input costs and direct machinery costs) tended to be highest in deep tillage approaches.

Table 26. Field details for year 9 (2013-2014).

Trial Id	**WW14-002**	
Cropping	Winter cropping	Winter oilseed rape (*cv*. Incentive)
	Spring cropping	Spring Oats (*cv*. Conway)
	Continuous wheat	Winter wheat (*cv*. Santiago)
	Alternate fallow/wheat	Cover crop fallow (mustard)
Cultivations	Shallow tillage	Sumo Trio (04/09/13), working with legs raised and discs (10 cm).
	Deep tillage	Sumo Trio (04/09/13), working with discs and deeper legs (20 cm).
	Managed approach	See Appendix A
	Annual plough	Ploughed (03/09/2013)

Table 27. Plant population and ear count summary information from STAR year 9 (2013/2014).

	Plants/m^2 (Assessed on 08/01/14 and 02/05/14)				Ears/m^2 (Assessed on 27/06/14)			
	Winter (OSR)	Spring (oats)	Cont (WW)	Alt Fallow	Winter (OSR)	Spring (oats)	Cont (WW)	Alt Fallow
Plough	95*	156	137	-	-	-	398	-
Managed	21	158	171	-	-	-	404	-
Shallow	77	130	198	-	-	-	415	-
Deep	72	125	166	-	-	-	428	-
Average	66	142	168				411	
LSD	99.6	42.8	32.1	-	-	-	38.4	-
CV %	5.5	15.1	9.6	-	-	-	4.7	-

* *It was noted that there were a significant number of volunteers in this treatment.*

Table 28. Yield and margin summary information from STAR year 9.(2013/2014).

	Yield (t/ha)				Gross margin – machinery cost (£/ha)			
	Winter (OSR)	Spring (oats)	Cont (WW)	Alt Fallow	Winter (OSR)	Spring (oats)	Cont (WW)	Alt Fallow
Plough	4.68	6.47	10.66	-	774	250	664	-
Managed	4.12	6.21	10.54	-	719	284	693	-
Shallow	3.78	6.27	10.73	-	624	302	728	-
Deep	4.67	5.22	10.38	-	861	185	674	-
Average	4.31	6.04	10.58	-	745	255	690	-
LSD t/ha	0.58	0.71	0.96	-				
CV %	6.4	5.9	4.5	-				

Margins based on diesel, 68ppl; nitrogen, 72p/kg N; wheat at £120/t; OSR at £280/t; oats £100/t.

5.10 Year 10 (2015) Summary

In year 10 (2014/15) the STAR project was in winter wheat (*cv*. Skyfall) (Table 29) and all population levels were good (Table 30). The higher levels of sunshine duration during June and July are likely to have contributed to some notably high first and continuous wheat yields. Soil penetration data has been collected across the project and differences between systems continued to remain apparent, in particular, comparing cultivation approaches, irrespective of rotation, data indicates that the shallow cultivation again resulted in tighter soils compared to the plough tillage in 2014/15. In year 10, the highest crop yields were generally associated with the managed approach. There was little or no difference in grain quality between either cultivation or rotational approaches. Margins (calculated as gross output minus input costs and direct machinery costs) continued to be highest in the managed and deep tillage approaches. Cultivation system choices demonstrate very little difference in gross margin between 'managed' approach and deep tillage. To date, shallow and plough cultivation practices have resulted in margins somewhat less than deep or managed approaches.

Table 29. Field details for year 10 (2014-2015).

Trial Id	**WW15-002**	
Cropping	All rotations	Winter wheat (*cv*. Skyfall)
Cultivations	Shallow tillage	Sumo Trio (04/09/14), working with legs raised and discs (10 cm).
	Deep tillage	Sumo Trio (04/09/14), working with discs and deeper legs (20 cm).
	Managed approach	See Appendix A
	Annual plough	Ploughed (04/09/14).

Table 30. Plant population and ear count information from STAR year 10 (2014/2015).

	Plants/m^2 (Assessed on 28/11/14)						**Ears/m^2 (Assessed on 06/07/15)**				
Tillage	Winter	Spring	Cont	Alt Fallow	Average		Winter	Spring	Cont	Alt Fallow	Average
Plough	115	137	132	130	122		370	379	347	354	363
Managed	119	135	123	102	121		352	369	346	371	363
Shallow	120	128	115	117	121		393	375	316	382	364
Deep	114	120	135	115	122		369	374	333	370	362
Average	117	130	126	116			371	374	336	369	
LSD	31.1						32.4				
CV %	15.3						5.4				

Table 31. Yield and margin summary information from STAR year 10 (2014/2015).

	Yield (t/ha)						**Gross margin – machinery cost (£/ha)**			
	Winter	Spring	Cont	Alt Fallow	Average		Winter	Spring	Cont	Alt Fallow
Plough	12.14	11.67	10.84	11.93	11.65		850	771	694	825
Managed	11.56	11.77	11.44	12.24	11.75		851	821	824	920
Shallow	11.74	11.61	11.04	12.11	11.63		872	834	788	917
Deep	11.89	11.68	10.98	12.23	11.70		878	830	769	919
Average	11.83	11.68	11.08	12.13			863	814	769	895
LSD t/ha	0.47									
CV %	2.5									

Margins based on diesel at 58ppl; nitrogen at 70p/kg N and wheat at £120/t.

6. Cross season findings

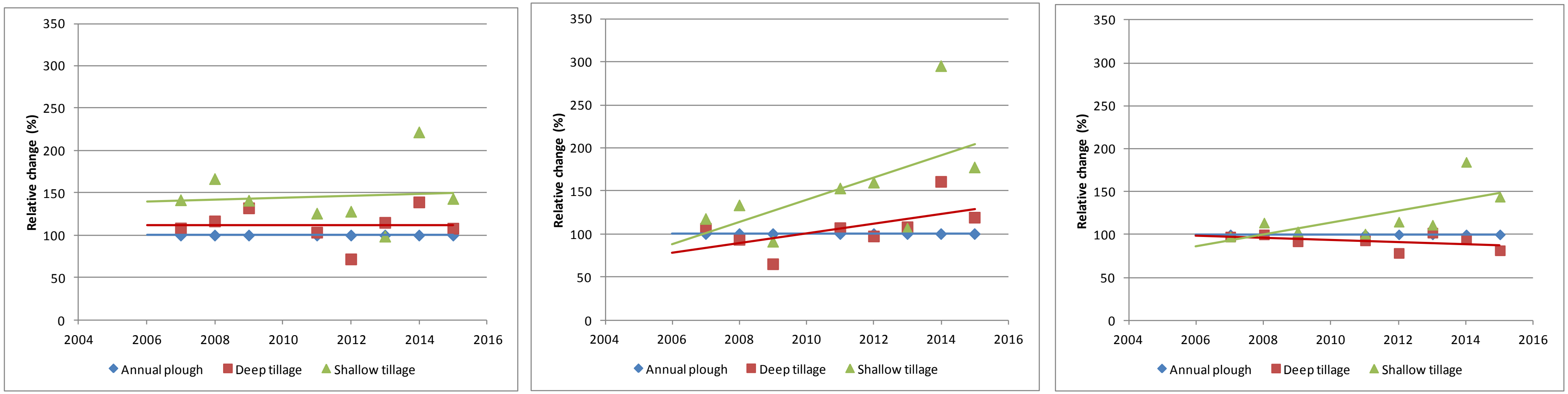
6.1 Soils

Weather conditions during the reporting period (2006-2015) showed significant inter-annual variation, for example, Met Office data for October 2012 indicated areas of East Anglia received approximately 175-200% of the 1971-2000 average rainfall for the period. In contrast, autumn 2009 indicated areas of East Anglia received approximately 80% of the 1971-2000 average rainfall for the period. These variations in weather patterns can result in a greater, or lesser, impact on soil structure and the success of subsequent crop establishment. It was noted that due to the excessively wet autumn in 2012, drilling was difficult and resulted in uneven crop establishment that was linked to the protracted wet weather.

The impact of both cultivation and rotation has been monitored closely over the experimental period. Specifically, soil strength, assessed using a cone penetrometer (to 35 cm depth) (this instrument measures the pressure required to move a probe through the soil profile; mimicking the passage of a root) to compare the impact of rotational and cultivation approach on soil strength. Annual measurements (typically taken during the winter period when the soil moisture is at field capacity) has indicated little impact of rotational approach on soil strength, but when comparing cultivaton approaches the shallow tillage has resulted in tighter soils compared to the plough tillage (with deep tillage and managed approach being intermediate). Therefore, there is a strong indication that, over the seasons, shallow tillage is continuing to exhibit increasing soil strength. The shallow tillage may be exacerbating this by delivering only a limited amount of mechanical alleviation of consolidation at depth.

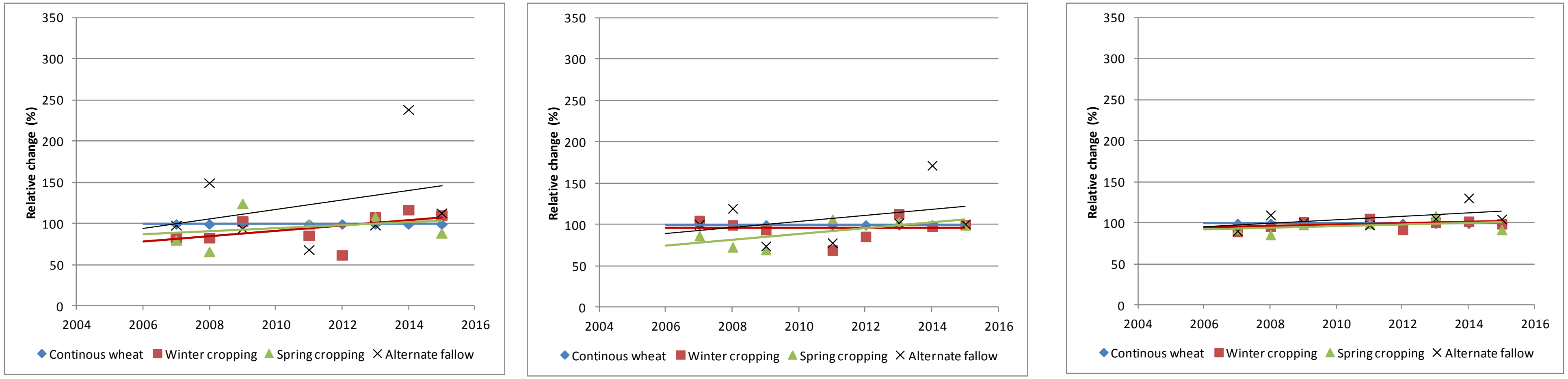
Soil strength data collected over the seasons 2007-2015 (excluding 2010 when conditions were too dry to collect data) have been analysed collectively to compare the impacts of cultivation and rotation on soil strength. The impact of cultivation on soil strength in the continuous wheat rotation is shown in Figure 1 (reported as the relative soil strength as a percentage of plough tillage). The depths compared were 10 cm (cultivation interface of shallow tillage), 20 cm (cultivation interface of deep and plough tillage) and 30 cm (below cultivation depth). Results show that across all three depths the shallow tillage resulted in soil that was tighter compared to the other tillage approaches. It is worth noting that at 20 cm depth the relative soil strength data for the shallow tillage suggests that it has become progressively worse over time e.g. in 2007 the shallow tillage had a relative strength of 118% compared to plough tillage; by 2015 this had increased to 177% compared to plough tillage. This trend has also been seen at 30 cm depth, but to a lesser degree, e.g. by 2015 the relative strength in shallow tillage was 144% compared to plough tillage. It is worth commenting that during 2014 shallow tillage showed a tendency to have much higher relative soil strength values compared to plough tillage and it is possible that this was a transient peak related to poor weather conditions in autumn / winter 2012.

Cultivation results comparing relative soil strength over other rotations (data not shown) also resulted in similar trends to that described above, with the shallow tillage becoming tighter over time. Little difference was apparent in relative soil strength between plough and deep tillage.



a) 10 cm b) 20 cm c) 30 cm

Figure 1. The impact of cultivation on soil strength in the continuous wheat rotation (as a relative % of plough tillage) at (a) 10cm (b) 20 cm and (c) 30 cm depth.



a) 10 cm b) 20 cm c) 30 cm

Figure 2. The impact of rotation on soil strength in plough tillage (as a relative % of continuous wheat at (a) 10cm (b) 20 cm and (c) 30 cm depth.

The impact of rotation on soil strength in plough tillage is shown in Figure 2 (reported as the relative soil strength as a percentage of the continuous wheat rotation). Findings showed some limited evidence of rotational differences, for example, when comparing plough tillage in the alternate fallow rotation there were some signs of tighter soils over time at 0cm depth (soil surface) *cf.* the continuous wheat rotation. However, at deeper depths (20 cm and 30 cm) relative soil strength variations across all rotations in plough tillage became much less apparent. There was little difference apparent from an analogous comparison of shallow tillage approaches across the rotations (data not shown). This would suggest that the rotational influence on soil strength is generally small with respect to cultivation approaches.

Comparing the different tillage approaches, it could be expected that shallow tillage may result in a higher soil bulk density (BD) compared to plough or deep tillage, due to shallow tillage delivering only a limited amount of mechanical alleviation at depth. Table 32 shows the BD measured in the continuous wheat rotation over a 5 year period (2011-2015); this shows little difference between approaches, with the average BD ranging from 1.11 g/cm^3 (deep tillage) to 1.18 g/cm^3 (plough tillage). Brady and Weil (2007)[*1] reported, for different soil textures, a range of bulk density values that would be suitable for root growth; the values reported here are all around the critical bulk density threshold of 1.10 g/cm^3 for the STAR soil type.

Table 32. The impact of tillage (in continuous wheat rotation) on soil bulk density (g/cm^3) at 10 cm depth.

	2010/11	2011/12	2012/13	2013/14	2014/15	Average
Plough tillage	1.11	1.02	1.21	1.34	1.20	1.18
Deep tillage	1.25	0.84	1.21	1.14	1.12	1.11
Shallow tillage	1.08	1.14	1.18	1.17	1.19	1.15

Further changes in soil physical structure and workability may be expected through the build-up of soil organic matter (SOM) through the retention and incorporation of crop residues over time. This may be expected where a shallow non-inversion tillage approach is used, whereby crop residues remain on, or close to, the soil surface, potentially leading to a gradual build up of SOM. Analyses of soil organic matter by the loss on ignition method (Table 33) resulted in little change in SOM between plough tillage and deep tillage (at 10 cm or 20 cm depths), but there is a small suggestion that SOM levels at 10 cm depth in shallow tillage may have increased marginally *cf*. plough tillage (with no correction for BD). Further results of soil organic matter over the time period are summarised in Appendix B; Soil nutrient and cropping details.

Table 33. The impact of tillage (in continuous wheat rotation) on soil organic matter (SOM %) at 10 cm and 20 cm depths in 2014/15.

	SOM (%) at 10 cm	SOM (%) at 20 cm
Plough tillage	3.4	3.4
Deep tillage	3.6	3.5
Shallow tillage	4.0	3.6

Further research using this well established platform is being supported by AHDB (Project RD 2012-3786) to test and demonstrate sustainable soil management: integration of major UK field experiments based on existing studies at the James Hutton Institute and NIAB TAG. The project to-date has collected numerous soil samples that require further analysis in the lab to measure mechanical impedance, bulk density, root seedling assays, soil resilience / slumping and soil carbon content. Detailed results will be reported on completion of the project. Further information on this project including an outline and key findings to-date can be accessed via the AHDB website (http://cereals.ahdb.org.uk/).

[*1] Brady, NC. and Weil, RR. (2007). The Nature and Properties of Soil. 14th Edition. New Jersey: Prentice Hall.

6.2 Crop performance and agronomy

Crop

Crop establishment and ear count data has been tracked each year since the start of the project. Long term monitoring of differences between cultivations and rotations are apparent. While there have been seasonal challenges in establishment, conditions have not been atypical to those being experienced by other local farms. The cross season analysis approach used in this section of the report uses relative differences between cultivation and rotation, which helps to account for variation due to seasonal differences.

Winter wheat plant count data depicted in Table 34 are presented as a percentage of the plough tillage for each rotational approach across five winter wheat cropping seasons (2007, 2009, 2011, 2013 and 2015). Mean results show only small differences in crop establishment between the cultivation techniques. Plough and deep non-inversion tillage systems produced similar plant numbers, whereas the managed and shallow non-inversion was marginally reduced by 4% and 6% respectively. Following through to ear counts, the plough, managed and deep non-inversion treatments were all similar, but again there was a small reduction in the shallow non-inversion treatments. These trends broadly follow the yield data responses.

Table 34. The impact of cultivation on plant and ear numbers relative to the plough (%) over 5 wheat crops in STAR.

	Plants (2007-2015)					Ears (2009-2015)				
	Winter	Spring	Cont	Alt Fallow	Average	Winter	Spring	Cont	Alt Fallow	Average
Plough	100	100	100	100	100	100	100	100	100	100
Managed	96	103	91	95	96	101	106	91	104	100
Shallow	88	103	83	102	94	100	103	79	103	96
Deep	99	105	91	105	100	97	103	90	111	100

Analogous analysis comparing each rotation relative to winter cropping for each approach, for both plant and ear count data, is presented in Table 35. Greater differences were seen between different rotations, whereby the continuous wheat has the lowest plant and ear counts relative to the other rotations, and the spring cropping and alternate fallow rotations were both similar or higher than winter cropping. These trends follow through to yield, where spring cropping often out-yielded other rotations in wheat years, and the continuous wheat tended to be lower yielding.

Table 35. The impact of rotation on plant and ear numbers relative to the plough (%) over 5 wheat crops in STAR.

	Plants (2007-2015)					Ears (2009-2015)				
	Plough	Managed	Shallow	Deep	Average	Plough	Managed	Shallow	Deep	Average
Winter	100	100	100	100	100	100	100	100	100	100
Spring	98	105	115	103	105	103	108	105	112	107
Cont wheat	99	95	93	93	95	90	81	71	83	81
Alt Fallow	101	101	119	107	107	94	97	97	109	100

Grass weeds

In the early years of the STAR project grass weeds were noted in the trial, but populations were negligible and were not of agronomic concern. By year 3 grass weed populations had increased in particular treatments. Notably grass weed heads (mainly meadow brome, but also barren brome, black-grass and wild oats) were increasingly apparent in the continuous wheat non-inversion treatments (Figure 3). No grass weeds of any species were observed in the ploughed continuous wheat plots. In year 4 a herbicide strategy strongly targeted towards brome management (combining an autumn residual herbicide and spring sulfonylurea) was imposed over the continuous wheat non-inversion treatments. Despite this, the trend of increasing grass weed numbers continued. Deep non-inversion continuous wheat treatments carried around 22 heads per m^2 while shallow non-inversion plots carried around 45 heads per m^2. Ploughed continuous wheat plots (along with other rotational approaches) continued to demonstrate negligible numbers of any grass weeds.

By year 5 (2010) grass weed numbers remained manageable in all rotations regardless of cultivation; however this was at an increased herbicide cost of > £100/ha in the continuous wheat non-inversion plots. While this herbicide programme reduced meadow brome heads to < 6 per $m^{2,}$ there was a clear impact in terms of yield reductions and on margin. Some grass weed ingress from the margins of the plots had been seen throughout the duration of the trial: this draws a parallel with 'headland invasion' in farm systems. Visual evidence also indicates that there was a spread of grass weeds from the margins by the drill and/or combine.

Considering all shallow non-inversion tillage treatments, cross-season analysis highlights a peak in grass weed head numbers in continuous wheat, alternate fallow and, to a lesser extent, spring cropping in year 8 (Figures 4). Establishment of the crop was difficult in autumn 2012 due to the wet weather conditions; East Anglia received approximately 175-200% of the 1971-2000 average rainfall for the period. This resulted in poor and uneven crop establishment, particularly in the shallow tillage treatments; these tillage treatments displayed a marked population reduction compared to other cultivation methods (Table 24). The reduced crop performance and competition in the shallow treatments potentially provided greater opportunity for weed ingress. Furthermore, while spring break crops can provide a useful opportunity for grass weeds management, the spring crop in year 7 was linseed. This performed poorly and was particularly uncompetitive, which consequently further augmented the potential for greater weed seed return to impact on the following first wheat.

It is interesting that a grass weed problem in specific treatments developed over only 5 years. The herbicide programme in year 4 used an autumn residual herbicide programme followed by Atlantis (mesosulfuron–methyl and iodosulfuron–methyl–sodium) to control the mixed grass weed burden in the non-inversion treatments. From year five onwards this was modified so the autumn residual programme was followed by a spring application of Broadway Star (pyroxsulam, cloquintocet–mexyl and florasulam), to manage the mixed grass weeds populations, and particularly the increasing meadow brome burden. This approach has kept the brome to manageable levels in the continuous wheat non-inversion treatments, but does demonstrate a heavy reliance on a combination of suitable herbicides.

The long term trends coming out of the STAR project in terms of grass weed management, indicate that continuous non-inversion approaches (particularly shallow non-inversion tillage) are associated with an increasing weed burden. Within other rotations, and across consistent cultivation approaches, other than in specific seasons, all other approaches have typically resulted in manageable grass weed populations.

Considering the managed approach strategies (decided each year in accordance with varying conditions), over the ten years of this trial, these have tended towards plough and deep non-inversion tillage (approx. 80% of cultivations in winter cropping, spring cropping and continuous wheat). The weed pressure in the managed approach has been minimal throughout. The project highlights the importance of assessment and informed decision making in determining a suitable cultivation approach year on year to suit the conditions, and the contributions this can make to rotational weed management.

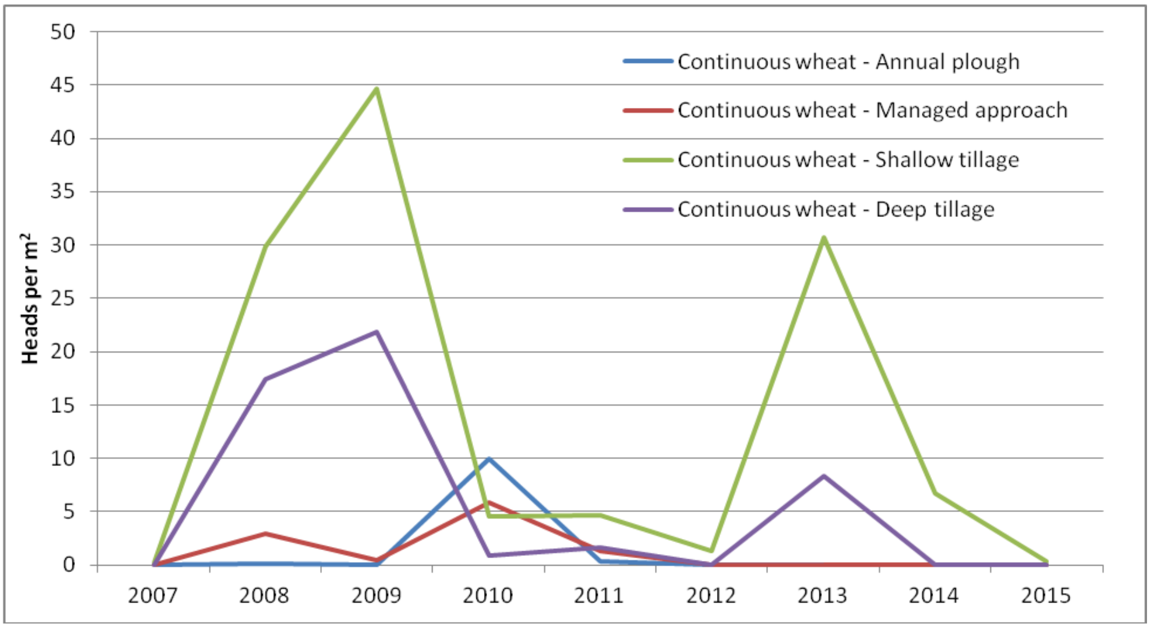


Figure 3. The impact of cultivation on grass weed head numbers.

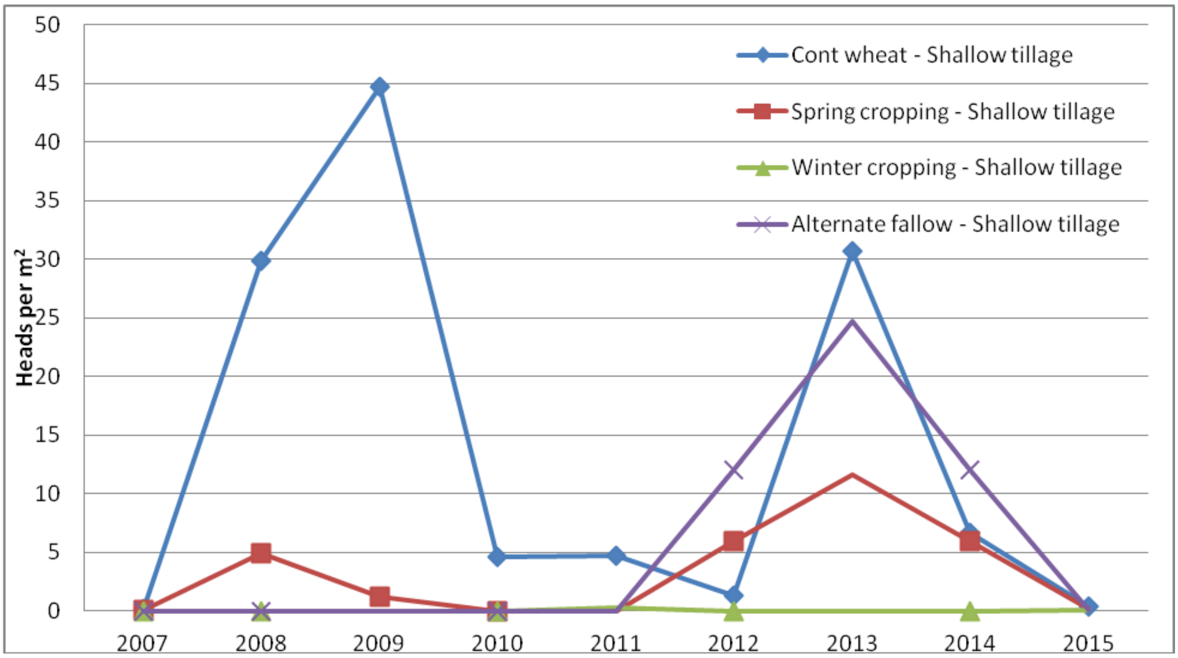


Figure 4. The impact of rotation on grass weed head numbers.

Mycotoxins

Mycotoxins are natural chemicals produced by certain fungi, notably fusarium species, that have varying levels of toxicity to humans and other animals. Fusarium can grow on a variety of different crops (causing head blight and seed-borne infection) and overwinter on crop debris and grass weeds / volunteers. The preceding crop, crop residues, seasonal conditions and agronomy are a few of the key factors which are likely to influence mycotoxin risk in wheat. Mycotoxin levels, specifically those produced by fusarium spp. (e.g. deoxynivalenol (DON)), have been measured regularly over the duration of the STAR project.

In year 2, mycotoxin analysis was carried out on all plots by Harper Adams University (formerly Harper Adams University College) and significant differences were found (Figure 5). The highest levels of DON were seen in the continuous wheat (particularly non-inversion treatments) and in the shallow tillage treatment of wheat following spring beans (established into wheat stubble with a strip cultivation and seeding system). Mean levels did not surpass those classed as unsafe for human consumption, although individual plots in the shallow continuous wheat treatment did exceed this mean. Given surface trash is important in the proliferation of mycotoxin causing pathogens, the higher levels found in the shallow and deep continuous wheat non-inversion treatments (compared to ploughing) is perhaps not surprising. Low levels of DON were found following oilseed rape and the alternate fallow rotation. In general greatest mycotoxin risks were clearly associated with the non-inversion treatments in the continuous wheat rotation.

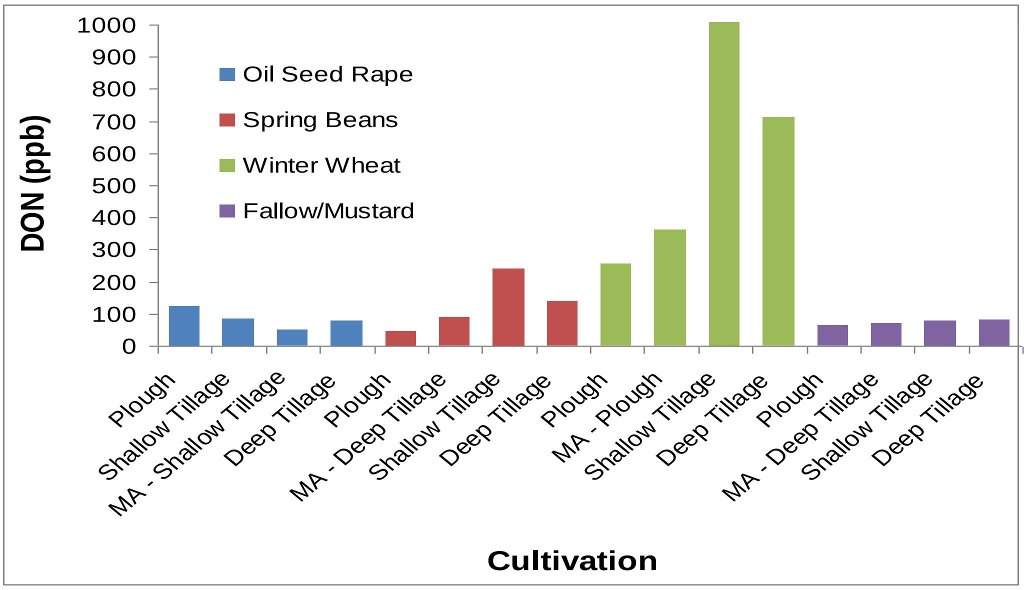


Figure 5. Mycotoxin analyses of all STAR plots in season 2 (2006/07). Analysis carried out by Dr Simon Edwards at Harper Adams University College.

In the following years similar trends were observed, and the highest mycotoxin levels were found in the continuous wheat shallow and deep non-inversion systems, however towards the latter years of the project values were low, often being either at or below the level of detection.

6.3 Yield and margins

Yield and margin data for individual seasons has been presented elsewhere in this report; however, yield and margin responses over time with respect to both rotation and cultivation practice are important, as is any interaction between the two with respect to the farming system. With the cultivation systems, the plough, deep and shallow non-inversion systems have remained constant through the study, although the managed treatment has varied with season. Of the consistent systems, soil inversion with ploughing represents the greatest level of soil disturbance, with progressively less disturbance from deep non-inversion and shallow non-inversion respectively.

Considering yield responses over time, Table 36 expresses mean yield responses for all crops in harvest years 2007-2015 as a percentage of the ploughed treatment yield for each rotational approach. While there was some variation between specific rotational approaches, generally the impact of cultivation on mean rotational yield was small. On average across rotational systems, ploughing tended to give the highest yields with a progressive numerical yield reduction with reducing tillage intensity. A yield reduction of c. 4% was noted between plough and shallow non-inversion tillage systems. The managed approach resulted in a similar mean yield to the plough based systems.

Table 36. The mean relative yield expressed as a percentage of the ploughed yield (%) for all crops in harvest years 2007 – 2015.

	Mean relative yield (% of plough)				
	Winter	Spring	Cont	Alt Fallow	
Plough	100	100	100	100	100
Managed	95	103	107	94	100
Deep	99	97	98	99	98
Shallow	93	93	100	98	96

Within the STAR rotational progression winter wheat is grown in alternate years. Over the 10 seasons reported in this study this has provided 5 iterations of wheat in the rotation and consequently the impact of primary cultivation practice on yield both within season and over seasons can be considered. A seasonal and cross seasonal analysis of wheat yields is presented in Table 37; considering yield as a percentage of ploughed yield averaged over seasons, there was a small numerical yield loss of 2%, comparing shallow to plough or deep non-inversion systems. It is notable that this loss in wheat crops considered alone is less than was seen across all crops in the rotation. These findings use mean wheat yield data from all rotations in a given season; however the winter and spring based rotations would be more common than the continuous wheat and alternate fallow treatments. Consideration of these rotational approaches separately in winter wheat does result in some physical differences in yield (the mean from the winter and spring treatments over this period was 9.42 t/ha compared to 8.79 t/ha for all rotations), however the percentage responses are consistent. Specifically, treating plough as 100% in both data sets, deep tillage was also 100% in both sets and the shallow tillage approaches were within 1% of each other. With regard to the cross season analysis presented in Table 37 (using wheat yield data from all rotations); statistically significant differences were noted in individual seasons and 'year' was significant (at $P<0.001$), however the 'treatment x year' interaction was not significant (NS). This suggests wheat yield potential is relatively robust in response to tillage, and while tillage practice may influence wheat yield in a given season in STAR, on average, tillage practice has not altered wheat yield when considered across a number of seasons.

Table 37. Winter wheat yield (t/ha) data and tillage practices in years 2 (2006/07), 4 (2008/09), 6 (2010/11), 8 (2012/13) and 10 (2014/15).

	Seasonal yield data (t/ha)						
Tillage	**Year 2**	**Year 4**	**Year 6**	**Year 8**	**Year 10**	**Mean yield (t/ha)**	**Yield (% of plough)**
Plough	8.64	8.51	6.83	8.61	11.64	8.85	100
Deep	7.78	9.00	7.40	8.30	11.69	8.82	100
Shallow	7.52	8.80	7.32	8.01	11.62	8.66	98
Mean	7.98	8.77	7.18	8.31	11.65	-	
LSD	0.45 ($P<0.0001$)	0.42 (NS) ($P=0.14$)	0.49 ($P<0.05$)	0.57 (NS) ($P=0.11$)	0.24 (NS) (P=0.69)	1.02 (NS) (P=0.91)	-

Cumulative margin data over the 10 year reporting period is presented in Table 38, this is expressed as mean margin responses for all crops in harvest years 2007-2015 in £/ha (based on spot prices in individual seasons). The table also presents the means result as a percentage based on the ploughed treatment. The margin findings show some similarity to those presented for yield over same period (e.g. shallow tillage again resulted in the lowest mean output with the managed approach performing well) however, there were also some key differences. Considering primary cultivation practice irrespective of rotation, while differences are again relatively small, ploughing tended to maximise yield over all crops the margins were greater in deep non-inversion and the managed approach. However, the difference between all systems was relatively modest at c. 6%. Considering the individual rotational approaches irrespective of primary cultivation practice, the winter cropping rotation resulted in the highest cumulative yield and the combination of winter cropping and deep non-inversion tillage resulted in the highest margin associated with any individual treatment.

Considering the margins for the wheat seasons alone suggests a similar ranking; if shallow non-inversion and deep non-inversion approaches as compared to plough based systems and ploughing is considered to represent 100%, then shallow and deep non-inversion approaches returned 104% and 107% of margin respectively over the 5 wheat crops (data not presented).

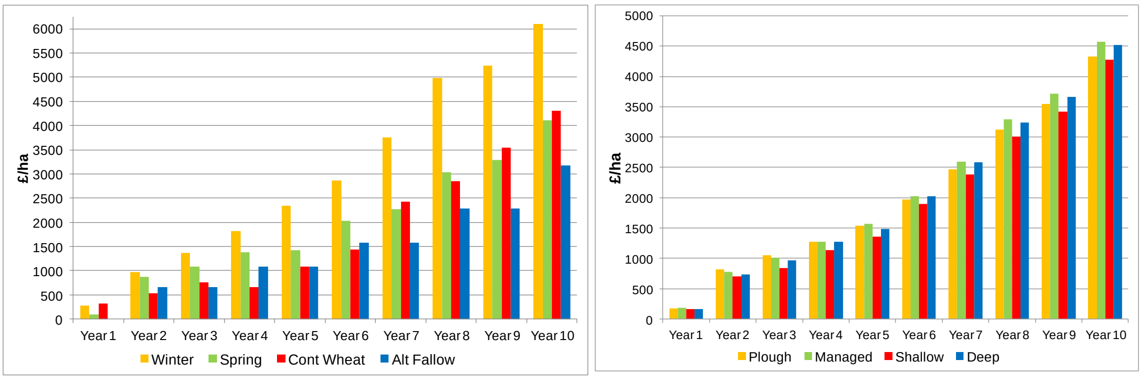
Rotational findings in STAR have also demonstrated the impact of break crops on the yield of following crops. For example in year 1 (2006) and year 5 (2010) the winter and spring break crops in STAR were winter oilseed rape and spring beans respectively; in each following season these break crops were followed by winter wheat. Considered across all cultivation systems the mean yields were oilseed rape (3.75 t/ha) and spring beans (2.91 t/ha) with wheat yields following oilseed rape being 8.00 t/ha and following beans 8.51 t/ha. For comparison the analogues mean yield of the continuous wheat was 5.91 t/ha; clearly demonstrating the break crop yield benefit. However, this finding demonstrates a yield response in winter wheat of 0.5 t/ha from the rotational use of spring beans compared to the use of winter oilseed rape.

Table 38. Cumulative margin expresses as £/ha and a percentage of the mean for each system for all crops in harvest years 2007 – 2015.

	Cumulative gross margin minus machinery cost (£/ha)					Mean as a % of plough
	Winter	Spring	Cont	Alt Fallow	*Mean*	
Plough	6217	3901	4026	3158	*4326*	*100*
Managed	6129	4373	4805	2982	*4572*	*106*
Deep	6611	4110	4043	3301	*4516*	*104*
Shallow	5431	4031	4359	3267	*4272*	*101*
Average	*6097*	*4104*	*4308*	*3177*		

Considering cumulative gross margins with respect to rotation, irrespective of cultivation, and cultivation, irrespective of rotation, are presented in Figure 6. The figures demonstrate that rotational choices are having a much bigger differential impact margin than cultivation choices and support the finding demonstrated previously that winter cropping is resulting in the highest cumulative margins.

Figure 6. Annual accumulation of gross margin with respect to rotation and cultivation practice.



The margins calculated in any individual season can also be used to gauge the variability in margin from each of the approaches; this variability is a function of the costs used as well the grain yields. The data presented in Table 39 is a relative margin over seasons expressed as a percentage of the mean margin in each given year. That is in any given season the margin in any treatment can be expressed as a percentage of the mean margin achieved for all treatments that year. This process can be repeated for each year of the study and mean data over all 10 seasons is as presented. Similarly, the variation between seasons can be used to calculate an error around that mean; this has been presented as a standard error of the mean.

The consideration of primary cultivation practice irrespective of rotation, would suggest in general systems were similar, however, the managed system resulted in the highest margins with the smallest level of variability (although it should be noted that the deep approach was similar), and the shallow non-inversion tillage treatment resulted in the lowest and most variable margin. Considering rotation irrespective of primary cultivation practice further supports the previous findings that winter cropping based rotational approaches resulted in the highest margins with among the lowest levels of variability. The spring cropping resulted in similar levels of variability, although the overall margin was lower and the continuous wheat and alternate fallow rotations resulted in notably greater levels of variability than either of the other two rotational approaches.

Table 39. Relative margin expressed as a percentage (± Standard Error of the Mean, SEM), based on a mean all crops in harvest years 2007-2015, based on individual seasonal margins expressed as a percentage of the mean margin in any given season.

	Relative margin (% of mean margin) ± SEM				
	Winter	**Spring**	**Cont**	**Alt Fallow**	***Average***
Plough	157 (±16)	82 (±11)	97 (±27)	59 (±20)	99 (±3)
Managed	157 (±16)	91 (±11)	116 (±23)	53 (±18)	104 (±2)
Shallow	127 (±18)	84 (±15)	108 (±23)	60 (±20)	95 (±4)
Deep	165 (±15)	86 (±15)	96 (±22)	62 (±22)	102 (±3)
Average	151(±12)	86 (±12)	104 (±23)	58 (±20)	

Cultivation systems used within the STAR project (Table 40) are based on the cost of primary cultivation. These indicate that costs associated with an inversion tillage approach (typically around £55/ha) are greater than those used in non-inversion tillage approaches (typically £30-40/ha). Therefore, under non-inversion tillage systems, typical savings of between £15-25/ha can be made. However, consideration should be given to other agronomic decisions e.g. weed control within some rotations, whereby, pressure on grass weed control could increase input costs thereby losing any saving from moving to non-inversion tillage approaches.

Table 40. Typical costs associated with primary cultivation operations from the STAR project (Morris and Stobart, 2014). Costs revised to Autumn 2016 values.

Establishment system	**Cost per ha (£)**	**Work rate (ha/hr)**	**Typical fuel consumption (litres/ha)**	**Fuel cost £/ha @ 40 p/litre**
5 furrow plough	54	0.8	29	12
3 m Sumo Trio (Depth 250 mm)	38	2.0	30	12
3 m Sumo Trio (Depth 100 mm)	28	4.0	27	11

The choice of cultivation operation can have a significant bearing on the working days available for specific soil types. Soil workability depends on interactions between climate and soil physical properties. For example, good working conditions on clay soils are commonly restricted to brief periods when the soil is neither too wet nor too dry for a good tilth to be obtained. Expected working days vary according to soil type and whether the year is a wet or dry season (Table 41); a wet season is typically assumed to occur with a frequency of one year in four. The expected working days required on a Hanslope series clay soil for a specific cultivation technique can be calculated. For example, on a 400 ha arable unit with 80 % of the land down to winter cropping cultivating 320 ha using a 5-furrow plough would take approximately 50 working days and for using a deep non-inversion tillage (20 cm depth) approximately 20 working days (assuming an 8-hour working day). It should be noted that the expected working days are for primary cultivation operations only and do not include secondary cultivations or drilling operations.

Work days / rates associated with cultivation operations in the STAR project (Table 40) and would be typical of many medium or medium-heavy soil types across East Anglia have been used to calculate expected working days to complete primary cultivations. On clay loams (Hanslope series) the expected working days for plough, deep non-inversion or shallow non-inversion approaches during the autumn are well within the good machinery work days (M.W.D's) for these soil types (Table 41). However, the expected working days in a wet spring (assuming 20 % of the land down to spring cropping) to work the land reduce greatly and in wet seasons could be constraining. In these situations, the timeliness of using non-inversion tillage would offer more flexibility allowing tillage operations to be completed with less risk of working the soil when it is too wet or too dry.

Table 41: Number of good machinery work days (M.W.D's) during the autumn and spring for a Hanslope series clay loam soil (taken from Hodge *et al*., 1984) and expected working days required for plough and non-inversion tillage.

	Autumn				Spring			
Type of year	**M.W.D's**	**Expected working days required for primary cultivations on 80 % of 400 ha arable farm *[1]**			**M.W.D's**	**Expected working days required for primary cultivations on 20 % of 400 ha arable farm *[2]**		
		5-furrow plough	Deep non-inversion	Shallow non-inversion		5-furrow plough	Deep non-inversion	Shallow non-inversion
Normal	101	50	20	10	33	13	5	3
Wet	79				12			

M.W.D's = Number of good machinery work days during the period.
*[1] Assumes a typical 8 hr working day and 80 % of land down to winter cropping.
*[2] Assumes a typical 8 hr working day and 20 % of land down to spring cropping.

7. Knowledge Exchange

The STAR project continues to attract a high level of interest regionally, nationally and increasingly internationally. Traditionally project findings have been focused mainly at farmer audiences, but engagement with students, researchers, policy makers and other industry stakeholders have become increasingly evident as the project has developed.

Outputs have been primarily delivered through NIAB TAG targeting both NIAB members and open information provision to wider audiences. However, outputs have also been delivered in conjunction with other organisations (e.g. collaborations with Easton and Otley College, LEAF, AHDB and other research collaborators). Examples of types of output delivered have included:

- <u>Briefing sessions</u>: STAR outputs are presented regularly as part of NIAB technical briefings to internal staff groups and to external parties (e.g. agronomist and industry briefings).
- <u>Media articles</u>: the project has featured in a range or articles in the farming press (e.g. Farmers Weekly, Farmers Guardian and Farmers Guide among others) as well as in local press and regularly with the NIAB Landmark magazine (going to c. 3,000 NIAB members).
- <u>Open events</u>: a formal annual open event is held at the STAR site each season. This has typically attracted 60-70 participants (mainly farmers) and has been very well regarded with very high percentages scores for relevance of information and uptake.
- <u>Project fliers</u>: a STAR project flier has been produced and is regularly updated. This provides a map of the site, a description of the treatments and an overview of main findings.
- <u>Published papers</u>: papers either directly on the STAR project or using data from STAR project have been published for a number of journals and events. It is estimated around 7 papers have been produced to date.
- <u>Reports and web material</u>: an annual report is produced for STAR and made available on line and by request. Periodically other web based information has also been developed.

- Research liaison: increasingly external research groups are seeking to use the STAR platform. This has included requests for information and field samples from UK and European research organisations (e.g. PhD students and research projects at various universities) and commercial research (e.g. recent studies monitoring the impact of system on slug populations).
- Results presentation: this has been a key dissemination route for STAR and findings have been presented a number of events ranging from scientific conferences (e.g. The European Society of Agronomy and AAB conferences), Industry events (e.g. distributor and AHDB events), NIAB membership activities (e.g. NIAB results conferences both regionally and nationally) and farmer discussion groups (e.g. local NFU and other group meetings).
- Student engagement: STAR outputs have been used in a number of student engagement activities, but specifically in field and lecture based sessions with Easton and Otley.
- Training events: STAR data and key findings have been widely incorporated into training material. This includes (for example) material developed for the Artis training initiative and delivered to the NIAB led Professional Development Training for Farmers groups.

The STAR project continues to be guided by an independent steering committee made up of local farmers and agronomists as well as NIAB TAG researchers. The committee meets 2-3 times pa. The minutes of each meeting include a knowledge exchange log as a standing item.

8. Key points and conclusions

The findings from STAR both in individual seasons and collectively over the progression of the project provide a unique data set and narrative, comparing key options around different cultivation and rotation systems for sustainable arable production on a heavy soil site. STAR also continues to deliver new information and as the iterations of different crops build in the rotation further cross season analysis can be developed. Equally, as new break crop inclusions or differing pairings / sequences are included, this allows for follow crop impacts to be better assessed. It should also be remembered that STAR continues to be an outstanding platform for other future research; potentially considering differing rotational constructions (such as second cereal inclusions), alternative soil management approaches (possibly around trafficking or amendments) or as a platform for new research areas (perhaps around soil biology). This fully replicated and well quantified site, delivers a comparison of contemporary arable system approaches using farm scale equipment and techniques, providing a very powerful research, education and knowledge exchange tool.

In summary, findings to date from this long term rotational systems study examining the interaction between four different rotations and four different cultivation methods have demonstrated clear impacts of rotation and cultivation decisions on key agronomic and production drivers, including (but not limited to): weed burden, soil condition and mycotoxin risks. However, the impacts on yield, margins and sustainability of systems are among some the chief outputs. With regard to yields, in general, the highest yields considered over all crops have been associated with plough based systems; although findings for wheat demonstrate much less impact of primary tillage regime on yield with non-inversion systems performing well. With regard to rotational gross margins, the winter cropping systems have resulted in highest margins often with lower variability compared to other approaches. Considering cultivation approach differences in gross margin have been smaller than those observed for rotation and the managed approach has performed well (that is making an informed decision on primary cultivation based on the crop, field conditions and other agronomic considerations such as grass-weed management on a seasonal basis). However, of the consistent systems (i.e. where the same approach is used every season), the deep non-inversion tillage has performed well giving similar yields, margins and variability to the managed approach. Regarding key findings and points from long term assessments these may be summarised as follows:

Key soils findings:

- Changes in soil bulk density with respect to tillage approaches have been small and remained within the key threshold for adequate root growth in all tillage approaches.
- The impact of tillage approaches on soil organic matter have generally been small, with a suggestion that organic matter in the top 10 cm in the shallow tillage is slightly greater than plough tillage. No substantial changes in SOM at 20 cm depth have been observed between tillage approaches.
- Results comparing soil strength with respect to tillage approach have shown a substantial change in the shallow tillage compared to plough tillage resulting in tighter soils. This trend has been observed both in the continuous wheat rotation and across all rotations.
- One observation that is surprising is that as well as tighter soils being apparent in the shallow tillage approach, the relative soil strength over time has also increased substantially when compared to plough tillage.
- Results comparing soil strength with respect to rotation would suggest that rotational impacts on soil strength are minimal with little differences apparent between plough tillage or shallow tillage approaches.

Key agronomy findings:

- Long term mean differences in crop establishment (plant counts) and ear numbers between the cultivation techniques are small; although some reduction in shallow non-inversion treatments were noted for both parameters.
- Data expressed as a mean long term relative percentage indicates continuous wheat crop establishment and ear counts to be consistently lower compared to other rotations.
- Grass weed populations at the initiation of project were low, however by year 3 numbers had increased markedly through the impact of practice changes. The greatest issues have been apparent in the continuous wheat non-inversion treatments, although it is worth noting that grass-weed issues have been less of a problem in the other rotation treatments and where ploughing has been retained in the continuous wheat rotation.
- A range of other factors have also had an influence on weed burdens in the project; including seasonal variations, spring crop choice and cultivation decisions, as well as herbicide inputs. The managed approach in the continuous wheat (and across rotations) has generally performed well, highlighting the importance of assessment and informed decision making in determining a suitable annual cultivation approach to suit the conditions.
- Previous crop, crop residues and agronomy are key factors affecting mycotoxin risks. Mycotoxin levels were typically highest in shallow non-inversion tillage continuous wheat.

Key yield and margin findings:

- On average across rotational systems and crops, ploughing has tended to give the highest yields, with a c. 4% yield reduction noted between plough and shallow non-inversion tillage systems. Considering winter wheat alone, there was a small numerical yield loss of c. 2%, comparing shallow to plough or deep non-inversion systems.
- With regard to wheat yield in response to primary tillage; statistically significant differences were noted in individual seasons and 'year' was significant, however the 'treatment x year' interaction was not significant (NS); suggesting that tillage practice in this study has not altered wheat yield significantly when considered across seasons.
- Considered over all crops the margins were greatest in the managed approach, closely followed by the deep non-inversion; however, the difference between all systems was relatively modest at c. 6%.
- Of the rotations, the winter cropping rotation resulted in the highest cumulative yield and the combination of winter cropping and deep non-inversion tillage resulted in the highest margin associated with any individual treatment.
- Considering primary cultivation practice irrespective of rotation, would suggest that the managed system resulted in the highest margins with the smallest level of variability (although the deep approach was similar), and the shallow non-inversion tillage treatment resulted in the lowest and most variable margin.

Appendix A – Managed approach summary

	Winter cropping	**Spring cropping**	**Alternate fallow**	**Continuous Wheat**
2006 WW+break	Sub-cast (20cm) Rolls *As deep*	Plough Spring tine Cultivator drill *As plough*	None	Plough Cultipress (x1) Cultivator drill Rolls *As plough*
2007 WW	Sumo (10cm) Cultivator drill Rolls *As shallow*	Sumo (20cm) Cultivator drill Rolls *As deep*	Sumo (20cm) Cultivator drill Rolls *As deep*	Plough Combi-drill Rolls *As plough*
2008 WW+break	Seed broadcast Plough Cultipress (x1) -	Plough Combi-drill *As plough*	None	Sumo (20cm) Cultipress (x1) Cultivator drill *As deep*
2009 WW	Sumo (20cm) Cultipress (x1) Cultivator drill *As deep*	Plough Cultipress (x2) Cultivator drill *As plough*	Plough Cultipress (x2) Cultivator drill *As plough*	Plough Cultipress (x2) Cultivator drill *As plough*
2010 WW+break	Sub-cast (20cm) Rolls *As deep*	Plough Claydon drill *As plough*	Combi-drill All approaches	Plough (20cm) Cultipress (x2) Cultivator drill Roll *As plough*
2011 WW	Sumo (10cm) Cultivator drill Rolls *As shallow*	Sumo (10cm) Cultivator drill Rolls *As shallow*	Sumo (20cm) Cultipress (x1) Cultivator drill *As deep*	Sumo (20cm) Cultipress (x1) Cultivator drill *As deep*
2012 WW+break	Plough Claydon drill As plough	Sumo (20cm) As deep	Combi-drill All approaches	Sumo (20cm) Cultipress (x1) Cultivator drill As deep
2013 WW	Sumo (20cm) Cultipress (x1) Combi drill *As deep*	Sumo (20cm) Cultipress (x1) Combi drill *As deep*	Sumo (10cm) Cultipress (x1) Combi drill *As shallow*	Sumo (20cm) Cultipress (x1) Combi drill *As deep*
2014 WW+break	*Sub-cast (low disturbance)* -	*Sumo (20cm) Power harrow Drill* *As deep*	*Combi-drill* All approaches	Sumo (20cm) Cultipress (x1) Tine drill As deep
2015 WW	Sumo (10cm) Power Harrow (x1) Weaving tine drill *Roll* *As shallow*	Plough Power Harrow (x2) Weaving tine drill Roll *As plough*	Sumo (20cm) Power Harrow (x1) Weaving tine drill *Roll* *As deep*	Sumo (20cm) Power Harrow (x1) Weaving tine drill *Roll* *As deep*

Appendix B – Soil nutrient and cropping details approach summary

	Soil nutrients - Available N (kg/ha), P (mg/l), K (mg/l), Mg (mg/l), soil pH and OM %)*	Sowing date	Harvest date
2006 WW+break	N-N/A; P-N/A ; K-N/A: Mg-N/A; pH-N/A; OM%-N/A (0-15 cm)	WW – 04/10/2005 WOSR – 31/08/2005 (Drilled), 07/09/2005 (Broadcast) SBeans – 03/02/2006 Mustard – 12/05/2006	WW – 29/08/2006 WOSR – 24/07/2006 SBeans – 29/08/2006
2007 WW	N-N/A; P-N/A ; K-N/A: Mg-N/A; pH-N/A; OM%-N/A (0-15 cm)	WW – 15/09/2006 (1st WW), 16/10/2006 (Cont WW)	WW – 29/08/2007
2008 WW+break	N-N/A; P-N/A ; K-N/A: Mg-N/A; pH-N/A; OM%-N/A (0-15 cm)	WW – 14/10/2007 WBeans – 25/10/2007 SOats – 04/04/2008 Mustard – 10/04/2008	WW – 28/08/2008 WBeans – 28/08/2008 SOats – 16/09/2008
2009 WW	N-40 ; P-12 ; K-103 : Mg- 46; pH- 7.6; OM%- 2.8 (0-15 cm)	WW – 02/10/2008	WW – 14/08/2009
2010 WW+break	N-N/A ; P-37 ; K-144 : Mg- 46; pH- 7.9; OM%- 2.6 (0-15 cm)	WW – 06/10/2009 WOSR – 29/08/2009 SBeans – 24/03/2010 Mustard – 13/04/2010	WW – 09/08/2010 WOSR – 09/08/2010 SBeans – 02/09/2010
2011 WW	N-51 ; P-12 ; K-127 : Mg- 41; pH- 8.1; OM%- 2.3 (0-15 cm)	WW – 14/10/2010	WW – 15/08/2011
2012 WW+break	N-89; P-20; K- 137: Mg- 74; pH- 7.1; OM%- 2.5 (0-10 cm) and 2.6 (20 cm)	WW – 06/10/2011 WBeans – 15/10/2011 Linseed – 16/04/2012 Mustard – 16/04/2012	WW – 22/08/2012 WBeans – 07/09/2012 Linseed – 07/09/2012
2013 WW	N-38; P-12; K- 136: Mg- 52; pH- 7.9; OM%- 5.5 (0-10 cm) and 5.5 (20 cm)	WW –06/10/2012 and 16/10/2012	WW – 27/08/2013
2014 WW+break	N-35; P-11; K- 104: Mg- 56; pH- 7.2; OM%- 3.8 (0-10 cm) and 3.7 (20 cm)	WW – 09/10/2013 WOSR – 06/09/2013 SOats – 27/03/2014 Mustard – 01/04/2013	WW – 30/07/2014 WOSR – 21/07/2014 SOats – 31/07/2014
2015 WW	N-33; P- 21; K- 109: Mg- 50; pH- 7.6; OM%- 3.4 (0-10 cm) and 3.4 (20 cm)	WW – 02/10/2014	WW – 08/08/2015

**Soil nutrient results taken from ploughed continuous wheat treatment.*