Final Report

Management of Rotations, Soil Structure and Water

(Rotations Research Partnership)

Work Package 1 (WP1):

The Grower Platform

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2. WORK PACKAGE 1

This work package comprised three main areas of work:

1. The reinstatement of a long-term rotational manuring experiment at Broom’s Barn Suffolk (NIAB).
2. Replicated experiments testing the effect of compost or cover crops on potato and cereal yield at NIAB (NIAB).
3. A three-year series of fully replicated field-scale experiment testing the effect of cover crops on spring barley (James Hutton Institute).
4. Data collection and analysis from a grower survey (NIAB and the James Hutton Institute).
5. An agronomic and economic analysis of survey and experimental data (NIAB and the James Hutton Institute).

It should be noted that there was considerable overlap between WP3 and WP1 and these two work packages should be considered together

3. REINSTATEMENT OF LONG-TERM EXPERIMENT AT BROOM'S BARN

For cross referencing within summaries, the experiments at Broom's Barn are 2017-1 (Potatoes), 2018-23 (Spring Barley), 2019-47 (Spring Wheat) and 2020-73 (Winter Wheat).

3.1. Materials and Methods

3.1.1. Historic treatments

The long-term 'Number 2' experiment at Broom's Barn was started in 1965. It originally tested a three-course rotation of sugar beet, spring cereal and winter cereal. Each crop was replicated twice in large blocks. Each block was subdivided into 18 plots and each plot was 5.08 m wide and 15.95 m long (e.g., 0.02 acres). To each plot, combinations of inorganic nitrogen (N), phosphate (P), potassium (K) and sodium (Na) and farm yard manure (FYM) were added. For P and K, the rates applied were 0, maintenance (i.e. replacing the P and K removed in grain or roots) and double maintenance. Sodium chloride was applied to the sugar beet crop, as was FYM which was applied at *c.* 61 t/ha. The same fertilizer treatment combination was applied to each plot every year. Full details of the historic treatments can be found in Draycott *et al*. 1972 and 1978. The last application of FYM to the experiment was 9 November 2011 and the last experimental crops were grown in 2012. From 2013 to 2016 the field was uniformly cropped and received standard applications of inorganic fertilizer. The 2016 crop was winter oil seed rape.

3.1.2. Current experiments 2016-2020

The new experiment was designed to investigate the combined effect of historic applications of inorganic fertiliser and organic manure with a fresh application of FYM. To achieve this, four key treatments were selected (Table 1). These were then split in half and fresh FYM was applied to a randomly selected half. The FYM was applied on 7 October at a rate of 59.3 t/ha using a calibrated plot-spreader (Millcreek Manufacturing Co, Pennsylvania, USA). The weight of FYM being applied was checked by placing the spreader on load cells every time it was refilled. At the time of application, six random sub-samples of FYM were taken and sent to Natural Resource Management (NRM) for analysis using standard methodology. The experimental area was ploughed and sub-soiled on 21 October.

Table 1. Historic treatments used in current study. For phosphate and potassium, 1 is a maintenance dose (based on expected crop removal) and 2 is twice the maintenance dose. Sodium and FYM were only applied to the sugar beet crop

Treatment label	Nitrogen	Phosphate	Potassium	Sodium	Farm Yard Manure
N	1	1	1	1	0
P	1	2	2	1	0
S	1	1	1	1	1
T	1	2	2	1	1

3.1.3. Potato 2017 (Expt 2017-1)

Nitrogen (120 kg N/ha as ammonium nitrate) was broadcast by machine on 18 April and roto-ridged on 20 April. The experiment was planted with Maris Piper seed (40-50 mm) using a two-row Keyag-Gruse cup-planter on 25 April to give an intended within-row spacing of *c*. 40 cm (33 333 plants/ha). Irrigation was scheduled using the NIAB CUF Irrigation model so that soil moisture deficits were not allowed to be limiting and a total of 88 mm of irrigation was applied.

The effect of the treatments on plant emergence was monitored by counting the number of emerged plants in the middle two rows of each plot every 3 – 4 days until emergence was complete. Ground cover (GC) was measured weekly using a grid from *c*. 50 % plant emergence until the canopies had senesced in the autumn. Integrated ground cover was estimated by firstly calculating daily values GC by interpolating between the weekly measurements and then summing. Radiation absorption was calculated by assuming that daily absorbed radiation was the product of incident radiation and fractional GC and then summing. A single harvest was taken on 4 October to measure the effect of the FYM treatments on yield and quality. At harvest, an area of 2.25 m^2 plants was taken from the centre row of the plot leaving adequate discard areas at each end. The number of plants and mainstems was recorded and all tubers > 10 mm were retained for grading. The tubers were graded in 10 mm increments and the number and weight of tubers in each grade was recorded. A representative sub-sample (*c*. 1 kg) was taken from the grades with the largest yield (50-60 and 60-70 mm). This sub-sample was washed and chipped and then dried in a recirculating-air drying oven at 90 °C for a minimum of 48 hours to measure tuber DM concentration.

The effect of the treatments on emergence and ground cover development was analysed by fitting logistic curves to the data and then analysing the fitted parameters by analysis of variance. Harvest data were analysed using analysis of variance and treatment differences are only stated as significantly different if the probability of the differences occurring by chance were < 5 % ($P < 0.05$).

3.1.4. Spring Barley 2018 (Expt 2018-23)

In 2018, the residual effects of the recent and historic FYM applications were tested in a crop of spring barley. The barley crop (variety, Laureate) was planted at a seed rate of 160 kg/ha on 26 March 2018. A standard N application rate of 110 kg N/ha was applied to all plots in two applications on 17 April and 3 August. A few weeks before harvest, plots ends were demarcated by defoliating with herbicides and the centre-line of each plot was marked. The experimental plots were harvested by a plot-combine on 21 August 2018 with a harvest area of 6 m x 1.5 m.

3.1.5. Spring Wheat 2019 (Expt 2019-47)

In 2019, residual effects of the compost applications were tested in a crop of winter wheat. The winter wheat (*cv* Siskin) was planted on 17 November 2018 at a seed rate of 172 kg/ha. The experimental plots received a uniform N application rate of 222 kg/ha. A few weeks before harvest, plots ends were demarcated by defoliating with herbicides and the centreline of each plot was marked. The experimental plots were harvested by a plot-combine on 13 September 2019 with a harvest area of 3 m x 1.5 m.

3.1.6. Winter Wheat 2020 (Expt 2020-73)

The winter wheat (cv. Skyfall) experiment at Broom's Barn, received uniform application of agrochemicals and P and K fertilizer and a total of 213 kg N/ha in three splits. A few weeks before harvest, plots ends were demarcated by defoliating with herbicides and the centreline of each plot was marked. The plot size at Broom's Barn 6.0 × 1.5 m.

3.2. Results and Discussion

3.2.1. Analysis of the compost (2017-1)

Results of the FYM analysis are shown in Table 2. An application rate of 59.3 t/ha would have supplied 15.8 t/ha of FYM DM, 367 kg total N/ha and *c*. 6 t total C/ha.

Table 2. Analysis of compost at time of application

	Dry matter concentration (%)	Total N in DM (%)	Total C in DM (%)
Mean (n =5)	26.6	2.33	38.1
S.E.	2.43	0.253	1.58

3.2.2. Emergence and ground cover development (2017-1)

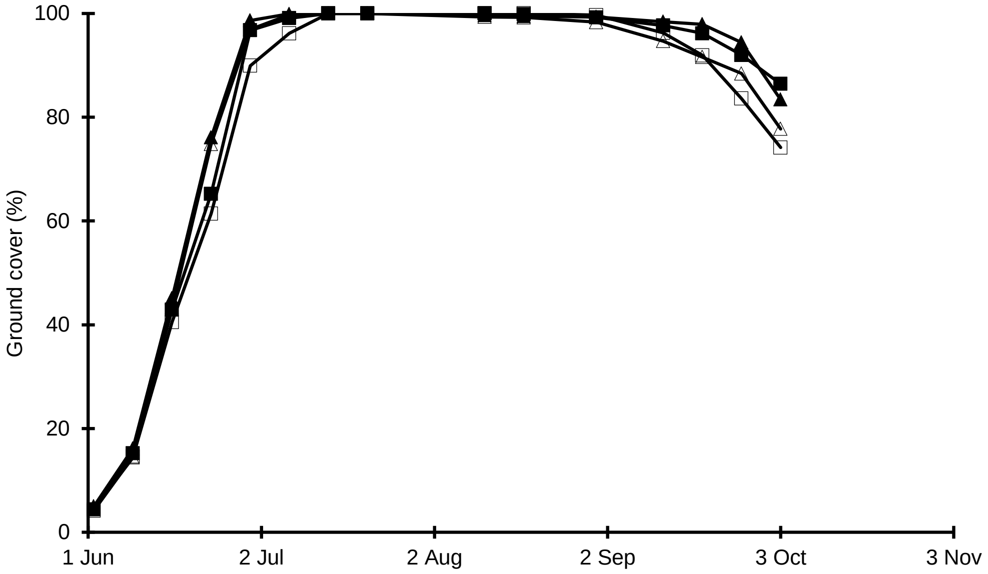
First emergence was noted on 26 May (38 days after planting (DAP) and 50% emergence was recorded on 27 May (39 DAP). All plots reached complete (100 %) emergence and there were no effects of the historic or new treatments on crop emergence. The main, combined effect of historic or recent FYM applications on the pattern of season-long GC development is shown in Figure 1. For all treatment combinations, 50 % GC was attained on 18 June (22 days after 50 % plant emergence). When compared with no previous applications of FYM, a history of FYM advanced the date of 50 % GC by *c.* 1 day. Similarly, a previous history of FYM application increased the maximum rate of GC expansion from 4.7 to 5.6 %/day when compared to an absence of historic FYM applications. Fresh FYM (applied in autumn 2016) had no effect on canopy expansion. At harvest in early October, the average GC was *c*. 80 %, with some canopies near-complete. Where FYM had been applied recently GC averaged 85 % compared with 76 % in the control plots.

The main effects of historic and recent applications of FYM on season-long integrated GC and radiation absorption are shown in Table 3. On average, season-long integrated ground cover and radiation absorption was 10558 % days and 15.16 TJ/ha, respectively. These values were broadly like those obtained in the compost experiment at NIAB (Section 4.1) which used the same stock of Maris Piper seed and had a similar date of 50 % plant emergence (23 and 27 May at NIAB and Broom's Barn, respectively). Numerically, a history of FYM together with a fresh application of FYM resulted in the longest-lived canopy and the largest radiation absorption; however, these effects were relatively small and non-significant.

Table 3. **Main effects of historic and recent applications of FYM on season-long integrated ground cover and radiation absorption at Broom's Barn, Suffolk**

Historic FYM	New FYM	Integrated ground cover (% days)	Radiation absorption (% days)
Mean		10558	15.16
None	None	10343	14.71
None	Applied	10606	15.05
Applied	None	10534	15.03.
Applied	Applied	10750	15.29
S.E. (20 D.F.)		83.4	0.117

Figure 1. **Effect of historic and recent application of farm yard manure on ground cover development in Maris Piper, Broom's Barn, Suffolk 2017. No historic or recent, □; No historic + recent, ■; historic no recent, △ and historic + recent, ▲.**



3.2.3. Yield and crop quality on 4 October, 130 DAE (2017-1)

At final harvest there was no effect of the treatments on plant or stem populations which averaged 30 460 and 94 100/ha, respectively. The number of mainstems per plant averaged 3.1 compared with 2.8 found in the compost experiment at NIAB. A history of FYM application caused a small, but significant increase in the tuber population (Table 4). Whilst freshly applied FYM was associated with a numeric increase in tuber population this effect was too small to be statistically significant. Despite having similar integrated GC and absorbing similar amounts of solar radiation, the average yield in the experiment at Broom's Barn was substantially larger than that found in the experiment at NIAB (72.4 compared with 62.3 t/ha, respectively). Use of FYM historically significantly increased total tuber FW yield by *c*. 7.0 t/ha and fresh FYM resulted in a 5.7 t/ha yield increase. There was no evidence of a synergistic effect between historic and recent application of FYM. The experimental average tuber DM concentration was 23.6 % (24.9 % at NIAB). Both historic and recent application of FYM resulted in agronomically and statistically significant decreases in tuber DM concentration. The average tuber DM yield was

17.0 t/ha (compared with 15.5 t/ha in the compost experiment at NIAB). In agreement with the data on canopy persistence and radiation absorption, neither historic nor fresh application of FYM had any significant effect on tuber DM yield. Therefore, in agreement with what was found in the experiment at NIAB, the observed differences in tuber FW yield were largely driven by the effects of FYM treatments on tuber DM concentration.

Table 4. Main effects of historic and recent application of FYM on components of yield and quality in Maris Piper, 4 October at Broom's Barn Suffolk

Historic FYM	New FYM	Tuber population (000/ha)	Tuber FW yield (t/ha)	Tuber DM concentration (%)	Tuber DW yield (t/ha)
Mean		403	72.4	23.6	17.0
None	-	383	68.9	24.7	17.0
Applied	-	423	75.9	22.5	17.0
S.E. (5 D.F.)		10.9	1.64	0.15	0.37
-	None	387	69.6	24.1	16.7
-	Applied	419	75.3	23.1	17.3
	S.E. (20 D.F.)	11.2	1.40	0.30	0.39
None	None	359	67.5	25.5	17.2
None	Applied	407	70.4	24.0	16.8
Applied	None	415	71.6	22.7	16.3
Applied	Applied	431	80.2	22.2	17.8
S.E. (20 D.F.)		15.6	2.16	0.34	0.54

3.2.4. Spring Barley 2018 (Expt 2018-23)

Experiments at Broom's Barn, Suffolk (2018-23) tested the residual effects of earlier FYM applications on the yield of spring barley and results are shown in Table 5. There was an indication (not statistically significant and possibly due to the limited degrees of freedom for the test) that grain yields were increased by historic application of FYM, but the application of FYM in autumn 2016 had no effect on grain yield.

Table 5. Experiment 2018-23, comparison of effects of historic application of farm yard manure with applications made in October 2016 on the yield of spring barley (t/ha at grain 15 % moisture) in 2018 at Broom's Barn, Suffolk (Expt 2018-23)

	0 t FYM/ha applied in 2016	58.8 t FYM/ha applied in 2016	Mean
No historic FYM	4.60	4.94	4.77
With historic FYM	5.86	5.20	5.53
Mean	5.23	5.07	5.15

S.E. (5 D.F., main effects of historic FYM) 0.104

S.E. (18 D.F., main effects of 2016 application of FYM) 0.199

S.E. (18 D.F., factorial combination of historic and 2016 applications of FYM) 0.234

3.2.5. Spring Wheat 2019 (Expt 2019-47)

The experiment at Broom's Barn, Suffolk (2019-47) tested the residual effect of previous FYM application on yields of winter wheat (cv Skyfall) and results are shown in Table 6. There was an indication (not statistically significant and possibly a consequence of the limited degrees of freedom for the test) that grain yields were increased by historic application of FYM, but the application of FYM in autumn 2016 may have decreased grain yield.

Table 6. Experiment 2019-47, comparison of effects of historic application of farm-yard manure with applications made in October 2016 on the yield of winter wheat (t/ha at 15 % moisture content) in 2019 at Broom's Barn, Suffolk

	0 t FYM/ha applied in 2016	58.8 t FYM/ha applied in 2016	Mean
No historic FYM	9.62	9.33	9.48
With historic FYM	10.25	9.48	9.86
Mean	9.93	9.41	9.67

S.E. (5 D.F., main effects of historic FYM) 0.197
S.E. (18 D.F., main effects of 2016 application of FYM) 0.187
S.E. (18 D.F., factorial combination of historic and 2016 applications of FYM) 0.271

3.2.6. Winter Wheat 2020 (Expt 2020-73)

The experiment at Broom's Barn, Suffolk (2020-73) tested the residual effect of previous treatments on yields of winter wheat and results are shown in Table 7. Grain yields were significantly increased by historic application of FYM. However, application of FYM in autumn 2016 was associated with a small (0.27 t/ha), but non-significant, decrease in grain yield.

Table 7. Experiment 2020-73, comparison of effects of historic application of farm yard manure with applications made in October 2016 on the yield of winter wheat (cv Skyfall) (t/ha at 15 % moisture content) in 2020 at Broom's Barn, Suffolk

	0 t FYM/ha applied in 2016	58.8 t FYM/ha applied in 2016	Mean
No historic FYM	5.62	5.05	5.34
With historic FYM	6.14	6.19	6.17
Mean	5.88	5.61	5.75

S.E. (5 D.F., main effects of historic FYM) 0.143

S.E. (18 D.F., main effects of 2016 application of FYM) 0.226

S.E. (18 D.F., factorial combination of historic and 2016 applications of FYM) 0.319

The effects of historic applications and a single recent application of FYM on a complete rotation are summarised in Table 8. These data indicate that, when compared with untreated controls, the historic applications of FYM have had numerically positive effects on yield in each of the four test-crops. In three of the four years, the yield increases were statistically significant. Overall, historic applications increased yield by *c*. 12 % relative to the control. A single application of FYM in October 2016, resulted in a significant increase in yield of the potato crop grown in 2017. However, numerically, cereal yields in 2018, 2019 and 2020 were reduced by FYM, but these differences were not significantly different. Overall, the single application of FYM in 2016 reduced rotational yield by one percentage point relative to the control.

Table 8. Summary of the main effect of historic applications or a single application of farm yard manure on potato and cereal yields at Broom's Barn, Suffolk. The *P* value is the probability of yield differences occurring by chance

		Main of effect of historic FYM			Main effect of 2016 FYM application		
		None	FYM	S.E. (5 D.F.) (*P*)	None	FYM	S.E. (18 D.F.) (*P*)
2017	Potato (t FW/ha)	68.9	75.9	1.64 (0.030)	69.6	75.3	1.40 (0.009)
2018	Spring barley (t/ha @ 15% MC)	4.77	5.53	0.104 (0.004)	5.23	5.07	0.199 (0.554)
2019	Winter wheat (t/ha @15% MC)	9.48	9.86	0.197 (0.227)	9.93	9.41	0.187 (0.059)
2020-73	Winter wheat (t/ha @15% MC)	5.34	6.17	0.143 (0.009)	5.88	5.61	0.226 (0.426)
	Mean (%)	100	112		100	99	

4. REPLICATED EXPERIMENT TESTING AMENDMENTS AND COVER CROP AT NIAB

During the experimental programme several fully replicated experiments took place at NIAB's Park Farm. Experiment 2017-2 in Field 27 tested the effect of compost on the yield and quality of a potato crop. Subsequent experiments tested the residual effect of the compost on spring-barley (2018-24) and winter wheat (2019-48). Experiment 2018-31 in Field 29 tested the effect of compost on a subsequent potato crop. Experiment 2018-32, also in Field 29, tested the effect of cover crop destruction dates on yield and quality of a subsequent potato crop. Experiments 2019-49 and 2019-50 were conducted in Field 30 and tested the effects of compost or cover crop destruction date, respectively. Finally, Experiment 2020-74 tested the effect of cover crop destruction date in Field 38/39.

4.1. Replicated Experiments at NIAB Field 27 with composts (2017-2, 2018-24 and 2019-48)

4.1.1. Materials and methods

4.1.1.1. Management and monitoring of potato experiment in 2017 (2017-2)

The compost experiment was conducted in Field 24 at NIAB and tested three rates of compost (0, 30 and 60 t/ha) in factorial combination with two rates of nitrogen (N) application (120 and 180 kg N/ha). Each treatment combination was replicated five times and allocated at random to blocks. Each plot was 5 m long by 6 rows (4.5 m) wide. The compost was applied by hand on 2 March and incorporated by ploughing (15 March). The experiment was power harrowed on 27 March and roto-ridged on 28 March. The experiment was planted, by hand, into the pre-formed ridges with Maris Piper seed (40-50 mm) on 5 April. The within-row plant spacing was 33.3 cm giving an intended plant population of 40 000/ha. The nitrogen treatments were applied by hand as ammonium nitrate immediately after planting and shallowly incorporated by raking. At the time of application, five random sub-samples of compost were taken and sent to Natural Resource Management (NRM) for analysis using standard methodology.

Plant emergence was monitored by counting the number of emerged plants in the middle two rows of each plot every 3 – 4 days until emergence was complete. Ground cover (GC) was measured weekly using a grid from *c*. 50 % plant emergence until the canopies had senesced in the autumn. Integrated ground cover was estimated by firstly calculating daily values of GC by interpolating between the weekly measurements and then summing. Radiation absorption was calculated by assuming that daily absorbed radiation was the product of incident radiation and fractional ground cover and then summing. A single harvest was taken on 18 October to measure the effect of the compost and nitrogen treatment on yield and quality. At harvest, 16 plants were taken from rows three and four of the six-row plot, leaving discard areas at each end. The number of plants and mainstems was recorded and all tubers > 10 mm were retained for grading. The tubers were graded in 10 mm increments and the number and weight of tubers in each grade was recorded. A representative sub-sample (*c*. 1 kg) was taken from the grades with the largest yield (50-60 and 60-70 mm). This sub-sample was washed and chipped and then dried in a recirculating-air drying oven at 90 °C for a minimum of 48 hours to measure tuber DM concentration.

The effect of the treatments on emergence and ground cover development were analysed by fitting logistic curves to the data and then analysing the fitted parameters by analysis of variance. Harvest data were analysed using analysis of variance and treatment difference are only stated as significantly difference if the probability of the differences occurring by chance were < 5 % ($P < 0.05$).

4.1.1.2. *Management and monitoring of spring barley in 2018 (2018-24)*

In 2018, a crop spring wheat crops was planted to quantify any residual benefits of the previous seasons compost applications. Due to the wet spring the spring wheat (variety, Chilham), was late planted (14 May 2018) at a seed rate of 172 kg/ha. The experimental plots received a uniform N application rate of 150 kg/ha. The experimental plots were harvested by a plot-combine on 3 September 2018 with a harvest area of 3 m x 1.5 m.

4.1.1.3. *Management and monitoring of winter wheat experiment in 2019 (2019-48)*

In 2019, residual effects of the compost applications were tested in a crop of winter wheat. The winter wheat (cv Siskin) was planted on 17 November 2018 at a seed rate of 172 kg/ha. The experimental plots received a uniform N application rate of 222 kg/ha. The experimental plots were harvested by a plot-combine on 13 September 2019 with a harvest area of 3 m x 1.5 m.

4.1.2. Results and discussion

4.1.2.1. *Analysis of the compost*

Results of the compost analysis are shown in Table 9. An application rate of 30 t/ha would have supplied 14.6 t/ha of compost DM, 4400 kg total C/ha and 327 kg total N/ha.

Table 9. Analysis of compost at time of application on 2 March 2017

	Dry matter concentration (%)	Total N in DM (%)	Total C in DM (%)
Mean (n =5)	48.6	2.24	30.2
S.E.	1.59	0.046	0.60

4.1.2.2. *Emergence and ground cover development of potato crop (2017-2)*

First emergence was noted on 16 May (41 days after planting (DAP)) and 50 % emergence was recorded on 23 May (48 DAP). All plots reached complete emergence and there were no effects of the compost or N treatments on emergence.

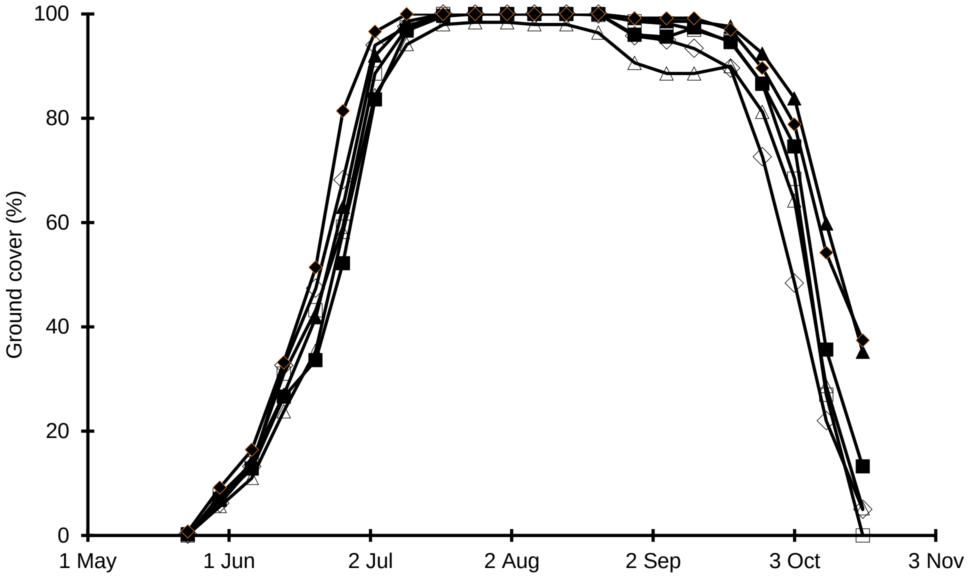
The effect of compost and N on the pattern of season-long GC development is shown in Figure 2. On average, 50 % GC was attained on 22 June (30 days after emergence). Applying 60 t/ha compost advanced the date of 50 % GC when compared with 0 or 30 t/ha. All treatments attained complete or near-complete GC. Canopy persistence (as estimated from the interval between attaining 50 % GC in the spring and senescing to 50 % GC in the autumn) averaged 107 days. The main effects of the compost and N treatments on season-long integrated GC and radiation absorption are shown in Table 10. Numerically, increasing the rate of compost application increased the GC persistence but this effect was small and not statistically significant. Increasing the N application rate from 120 to 180 kg N/ha significantly increased canopy persistence by *c.* 700 % days (i.e. equivalent to an extra week at 100 % GC).

Application of compost had no effect on radiation absorption but increasing the N application from 120 to 180 kg N/ha increased radiation absorption by 0.61 TJ/ha.

Table 10. Main effects of compost and N applications on season-long integrated ground cover and radiation absorption

	Integrated ground cover (% days)	Radiation absorption (TJ/ha)
Mean	10717	14.20
0 t compost/ha	10570	14.04
30 t compost/ha	10658	14.01
60 t compost/ha	10922	14.57
S.E. (20 D.F.)	194.4	0.184
120 kg N/ha	10354	13.90
180 kg N/ha	11080	14.51
S.E. (20 D.F.)	158.7	0.151

Figure 2. Effect of compost and N applications on ground cover development in Maris Piper, NIAB Field 24 2017. 0 t compost/ha, □; 30 t compost/ha, △ and 60 t compost/ha, ◇. Open symbols are 120 kg N/ha and shaded symbols 180 kg N/ha.



4.1.2.3. *Potato yield and crop quality on 18 October (148 DAE) in 2017-2*

At final harvest there was no effect of the treatments on either plant or mainstem populations which averaged 40000 and 111600/ha, respectively. When compared with no compost, applying 30 or 60 t/ha caused a small but significant increase in the total (> 10 mm) tuber population (Table 11). Increasing the amount of compost applied from 0 to 60 t/ha significantly increased total tuber FW yield by 6.9 t/ha (Table 11), but there was no effect of N application rate on tuber FW yield. When no compost had been applied there was an indication that increasing the N application rate from 120 to 180 kg N/ha was associated with a decrease in yield, however, this effect was probably anomalous. When compost had been applied, tuber DM concentration was reduced by *c*. 2 percentage points but increasing the N application rate had no effect on tuber DM concentration. Consistent with data on ground cover persistence and radiation absorption, the effects of compost and N rate on tuber DW yield were small and non-significant. The treatments had no effect on mean tuber size which averaged 62.9 mm or on tuber size distribution (mean coefficient of variation was 18.2 %).

Table 11. Main effects of compost and N applications on components of yield and quality in Maris Piper, 18 October

	Tuber population (000/ha)	Tuber FW yield (t/ha)	Tuber DM concentration (%)	Tuber DW yield (t/ha)
Mean	414	62.3	24.9	15.5
0 t compost/ha	391	58.8	26.2	15.4
30 t compost/ha	438	62.6	24.3	15.2
60 t compost/ha	413	65.7	24.1	15.8
S.E. (20 D.F.)	8.6	1.08	0.48	0.44
120 kg N/ha	408	61.9	25.0	15.5
180 kg N/ha	420	62.8	24.8	15.5
S.E. (20 D.F.)	7.0	0.88	0.39	0.36

4.1.2.4. NIAB F24 Spring Wheat (Expt 2018-24)

An experiment in Field 24 NIAB (2018-24) tested the residual effect of an earlier compost application (Spring 2017) on the yield of spring wheat and results are shown in Table 12. This experiment showed that there was no residual effect due to the differential N application applied to the potato crop, but yields were significantly increased when 60 t/ha of compost had been applied before the previous potato crop. The yield of plots that had received 30 t/ha appeared anomalously small.

Table 12. Experiment 2018-24, comparison of the residual effects of compost and N fertilizer applied in spring 2017 on the yield of spring wheat (t/ha at 15 % moisture content) in 2018 in Field 24, NIAB, Cambridgeshire (Expt 2018-24)

Application rate of compost in 2017 (t/ha)	Nitrogen application rate (kg N/ha) in 2017		
	120	180	Mean
0	2.94	3.50	2.72
30	1.94	3.04	2.49
60	3.19	3.51	3.35
Mean	2.69	3.02	2.85

S.E. (20 D.F., main effects of 2017 compost application) 0.209

S.E. (20 D.F., main effects of 2017 N application) 0.171

S.E. (20 D.F.,factorial combination of compost and N) 0.296

4.1.2.5. NIAB F24 Winter Wheat (Expt 2019-48)

An experiment in Field 24 NIAB (2019-48) tested the residual effects of an earlier compost application (Spring 2017) on the yield of winter wheat (cv. Siskin) and results are shown in Table 13. The experiment showed that there was no residual effect due to the differential N application applied to the potato crop nor a residual affect from compost additions in spring 2017. The yield of the treatment combination of 30 t/ha and 120 kg N/ha appeared anomalously small.

Table 13. Experiment 2019-48, comparison of the residual effects of compost and N fertilizer applied in spring 2017 on the yield of winter wheat (t/ha at 15 % moisture content) in 2019 in Field 24, NIAB, Cambridgeshire

Application rate of compost in 2017 (t/ha)	Nitrogen application rate (kg N/ha) in 2017		
	120	180	Mean
0	8.10	6.10	7.10
30	5.77	6.94	6.36
60	6.19	7.53	6.86
Mean	6.68	6.86	6.77

S.E. (20 D.F., main effects of 2017 compost application) 0.952

S.E. (20 D.F., main effects of 2017 N application) 0.777

S.E. (20 D.F.,factorial combination of compost and N) 1.346

4.2. Replicated Experiment at NIAB F29 with compost (2018-31)

4.2.1. Materials and Methods

4.2.1.1. Location and design

Experiment 2018-31 was conducted in F29 at NIAB, Cambridge (52.2342 °N, 0.0999 °E) on a sandy loam soil (60 % sand, 27 % silt and 13 % clay) with 8-20 % stone, 2.9 % organic matter content and a pH of 7.0. The P, K and Mg Indices were 3, 2 and 2, respectively. Consequently, no P, K or Mg fertilizer was applied prior to ploughing. The field was drilled with a cover crop of winter oats in September 2017 and ploughed on 19 April 2018 without desiccating. The experiment tested two compaction regimes (Uncompacted, Compacted), two irrigation regimes (Dry, Wet) and two rates of compost application (0, 30 t/ha) in factorial combination. Each treatment combination was replicated three times and allocated at random to blocks. Each plot was 9 m long by six rows (4.5 m) wide. There was a discard row between plots and a 1 m gap between plots as an irrigation guard. The compaction treatments were carried out on 19 April directly onto the ploughed soil. The soil was close to field capacity at plough depth at this stage. The treatments were imposed by driving a John Deere 6120R tractor with rear-mounted plot drill and fronted-mounted disc roller packer (total laden weight 7570 kg). The tractor ran on 340/85R/48 rear tyres at 25 PSI pressure and 340/85R/28 front tyres at 15 PSI over the entire area of the plot, so that by driving and reversing across the plot, each tyre compressed the soil twice. Using the Terranimo soil compaction model, this would be expected to result in major soil compaction to 55 cm depth and minor compaction to 70 cm given the soil water content and bulk density at the time of compaction. Following compaction, the area was spring-tined to a depth of 10-12 cm and then roto-ridged with a Rumptstad rototiller on 20 April. The two irrigation treatments were Dry, irrigated whenever the SMD reached 60 mm and Wet, irrigated whenever the SMD reached 25 mm. Application amounts varied from 16-24 mm in the Dry treatment (four irrigations totalling 84 mm) and from 16-28 mm in the Wet treatment (12 irrigations totalling 259 mm). Irrigation was scheduled using the CUF Potato Irrigation Scheduling Model based on meteorological data obtained from a Delta-T Devices weather station *c*. 450 m from the experiment. The two irrigation treatments were timed based on the mean SMD within each irrigation treatment combination. The irrigation was carried out using a diesel engine-driven Briggs VR4 90/400 hosereel and R50 boom equipped with Senninger LDN UP3 Single Pad nozzle dropper pipes to allow discrete irrigation between plots. The compost treatments were applied by hand on 14 March onto the growing oat cover crop and incorporated by ploughing (19 April). At the application rate of 30 t/ha, the compost supplied 16.0 ± 0.8 t/ha of DM, 343 ± 32.0 kg total N/ha, 144 ± 18.0 kg total P/ha, 210 ± 21.0 kg total N/ha and 4.7 ± 0.4 t total C/ha.

The experiment was planted by hand into the pre-formed ridges with Maris Piper seed (30 40 mm, tuber count 1714/50kg) on 25 April. The within-row plant spacing was 30 cm giving an intended plant population of 44 400/ha. Ammonium nitrate was applied at a rate of 200 kg N/ha post-planting, but pre-emergence, on 17 May. Herbicides and fungicides were applied as required to maintain the experiment free from weeds and blight.

4.2.1.2. Emergence, ground cover and soil sampling

Plant emergence was monitored by counting the number of emerged plants in the middle two rows of each plot every 3–4 days until emergence was complete. Ground cover (GC) was measured weekly using a grid from *c*. 50 % plant emergence until the canopies had senesced in the autumn. Integrated ground cover was estimated by calculating daily values of GC by interpolating between the weekly measurements and then summing these values. Radiation absorption was calculated by assuming that daily absorbed radiation was the product of incident radiation and fractional ground cover and then summing.

4.2.1.3. Sampling of potato crop

A single harvest was taken on 1 October to measure yield. At harvest, 10 plants were taken from rows three and four of the six-row plot, leaving discard areas at each end. The number of plants and mainstems was recorded and all tubers > 10 mm were retained for grading. The tubers were graded in 10 mm increments and the number and weight of tubers in each grade was recorded. A representative sub-sample (*c*. 1 kg) was taken from the grades with the largest yield (50-60 and 60-70 mm). This sub-sample was washed and chipped and then dried in a recirculating-air drying oven at 90 °C for 48 hours to measure tuber DM concentration. The effects of the treatments on emergence and ground cover development were analysed by fitting logistic curves to the data and then analysing the fitted parameters by analysis of variance. Harvest data were analysed using analysis of variance and treatment difference are only stated as significantly different if the probability of the differences occurring by chance were < 5 % ($P < 0.05$).

4.2.2. Results and discussion

4.2.2.1. Emergence and ground cover development

First emergence was noted on 22 May (27 DAP). Mean date of 50 % emergence was 26 May (31 DAP). The Compacted treatment reached 50 % emergence (52 DAP) 3 days later than Uncompacted (49 DAP). Adding compost had no effect on 50 % emergence and no treatments affected final emergence (which averaged 98 % of that intended).

The effect of the treatments on the pattern of season-long GC development is shown in Figure 3 and on season-long integrated GC and radiation absorption in Table 14. There was a consistent effect of soil compaction to reduce ground cover until the beginning of August (Figure 3a). Uncompacted crops began to senesce earlier than the Compacted, and there was a slight increase in light interception in Compacted treatments during September, but this was much less than the increase in light interception of Uncompacted crops earlier in the season. Compaction reduced ground cover duration by the equivalent of 8.8 days at full ground cover (Table 14). Irrigation increased the ground cover expansion from mid-June compared with treatments that did not receive their first irrigation until 2 July (Figure 3b). There was a small delay in complete canopy senescence in Wet compared with Dry crops. The overall effect of irrigation regime on ground cover duration and light interception was smaller than for compaction, *c*. 6 days at full ground cover (Table 14). Adding compost resulted in an increase in ground cover duration of 6 days at full cover, similar to the response to irrigation (Figure 3*c* and Table 14). Around the period of canopy closure (mid-July to mid-August), there was an interaction between compaction and irrigation treatments. Crops grown in compacted soil where the soil was kept dry had much lower ground covers during this period than Uncompacted, Wet plots. Frequent irrigation in Compacted plots overcame most of the effects of poor soil conditions on ground cover. Overlapping, but slightly after this period, there was an interaction between irrigation regime and compost application, in that compost application improved ground cover where soils were kept dry compared with no compost. The overall effects on seasonal light interception were small, but in favour of compost providing a greater advantage under dry conditions than when fully irrigated.

Figure 3. Effect of *(a)* compaction, *(b)* irrigation applications and *(c)* compost application on ground cover development. Uncompacted, Unirrigated, No compost ■; Compacted, Irrigated, Compost, □. Error bars based on 20 D.F.

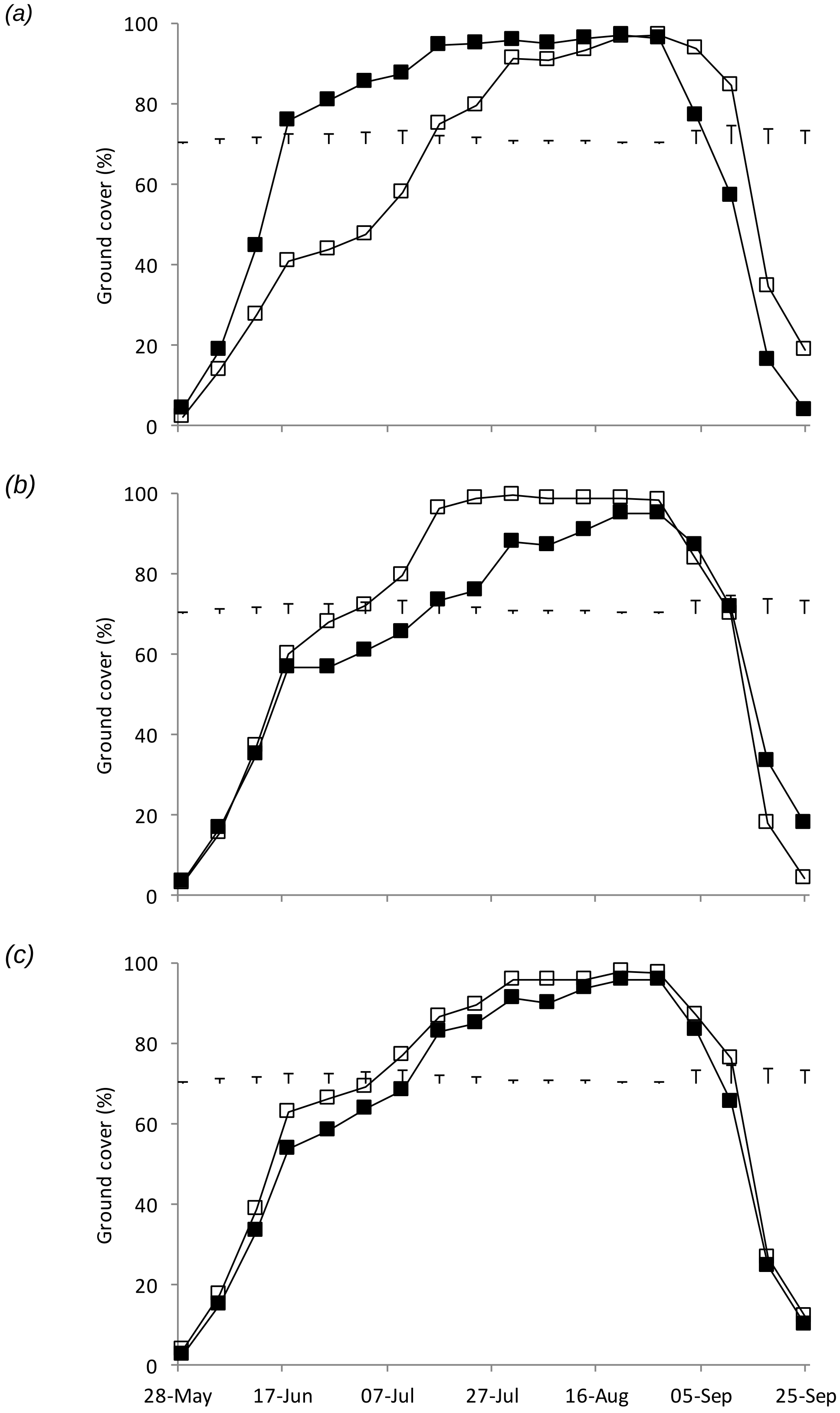


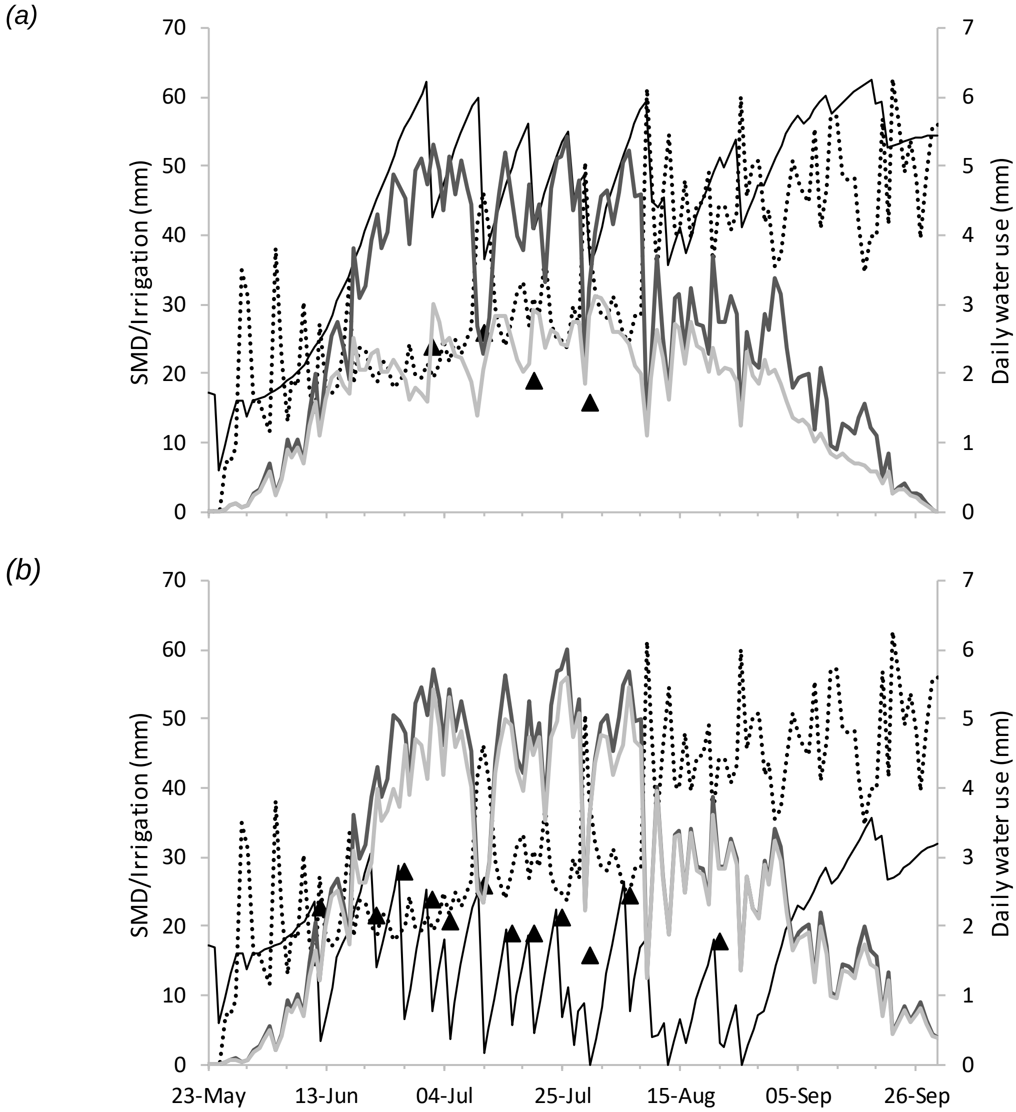
Table 14. Main effects of compaction, irrigation and compost treatments on season-long integrated ground cover and radiation absorption (Expt 2018-31)

Treatment	Integrated ground cover (% days)	Radiation absorption (TJ/ha)	Radiation use efficiency (TJ/t DM)
Dry	7839	13.2	0.766
Wet	8446	14.7	0.954
Uncompacted	8580	15.3	0.822
Compacted	7705	12.6	0.899
No compost	7838	13.4	0.862
Compost	8446	14.5	0.859
S.E. (20 D.F.)	134	0.24	0.0262

4.2.2.2. Soil moisture deficits and daily water use

The 2018 season was very hot and dry in June and July and evapotranspiration was much higher than the long-term average values for these months. Only 102 mm of rain fell between emergence and final harvest and none during the 4 weeks after tuber initiation. Consequently, demand for irrigation throughout June and July was high. The treatments were kept close to their intended SMDs, but the Wet treatments occasionally exceeded the intended owing to insufficient irrigation capacity (Figure 4).

Figure 4. Modelled soil moisture deficits, daily water use and irrigation. *(a)* Dry; *(b)* Wet. Data are means of both compaction and both compost treatments. Soil moisture deficit, ——; limiting soil moisture deficit, ----; irrigation, ▲; potential daily water use, ▬; actual daily water use, ▬.



4.2.2.3. Yield and crop quality at final harvest on 1 October

At final harvest there was no effect of the treatments on either plant or mainstem populations which averaged 44400 and 111800/ha, respectively. The total number of tubers was increased where soils were allowed to reach an SMD of 60 mm compared with keeping soil wetter (Table **15**). Total yield, yield > 40 mm and tuber DM yield were all increased with frequent irrigation compared with infrequent and having uncompacted soils rather than compacted (Table **15**). Frequent irrigation on average increased total FW yield by 15.6 t/ha, whilst compaction reduced total yield by only 5.6 t/ha. Compost application increased fresh and dry weight yields by 9.5 and 2.3 t/ha, respectively, in uncompacted soil but there was no effect on compost in compacted soils. There was no effect of any treatment on tuber DM concentration (Table 15). The canopies were almost dead at final harvest, but there was DM in the dead haulm not accounted for in calculating radiation use efficiency (RUE). Looking purely at RUE of tuber DM, frequent irrigation increased RUE compared with higher deficit irrigation (Table 14). Compaction increased RUE, possibly because of making the canopies shorter and slightly more determinate and increasing the harvest index (Table 14). Compost amendment had no effect on RUE.

Table 15. Effects of compost and N applications at NIAB on components of yield and dry matter concentration (Expt 2018-31)

Irrigation	Compaction	Compost	Total no. of tubers (000/ha)	Tuber FW yield (t/ha)	Yield > 40 mm (t/ha)	Tuber [DM] (%)	Tuber DW yield (t/ha)
Dry	Uncompacted	None	607	37.6	30.1	25.3	9.52
		Compost	649	43.6	36.2	25.7	11.22
	Compacted	None	610	35.5	27.6	25.6	9.00
		Compost	594	39.2	32.4	25.9	10.12
Wet	Uncompacted	None	582	53.7	48.4	25.5	13.65
		Compost	558	63.3	59.6	25.3	15.95
	Compact	None	568	52.5	47.4	26.0	13.62
		Compost	503	48.7	44.3	25.8	12.55
S.E. (20 D.F.)			32.4	2.38	2.31	0.61	0.632
Dry			615	38.9	31.5	25.6	9.97
Wet			553	54.6	49.9	25.6	13.94
	Uncompacted		599	49.6	43.5	25.4	12.59
	Compact		569	43.9	37.9	25.8	11.32
		None	592	44.8	38.3	25.6	11.45
		Compost	576	48.7	43.1	25.7	12.46
S.E. (20 D.F.)			16.2	1.19	1.16	0.31	0.316

4.3. Replicated Experiment at NIAB F29 with cover crops (2018-32)

4.3.1. Materials and Methods

4.3.1.1. Soils, management of cover crop, cultivations, and experimental design

The experiment was conducted in F29 at NIAB, Cambridge (52.2342 °N, 0.0999 °E) on a sandy loam soil (60 % sand, 27 % silt and 13 % clay) with 8-20 % stone, 2.9 % organic matter content and a pH of 7.0. The P, K and Mg Indices were 3, 2 and 2, respectively. Consequently, no P, K or Mg fertilizer was applied prior to ploughing. The previous crop was winter oats and was subsoiled at 38 cm depth on 12 September 2017. The field was drilled with a cover crop of winter oats at a seed rate of 70 kg/ha on 18 September 2017. No fertilizer was applied to the cover crop. The experiment tested three cover crop management regimes: no cover crop (cover crop sprayed out with glyphosate 7 days after emergence using a knapsack sprayer); cover crop allowed to grow until 9 March 2018 and then sprayed off; cover crop left growing until ploughing. Each treatment combination was replicated eight times and allocated at random to blocks. Each plot was 6 m long by six rows (4.5 m) wide. There was a 1 m access gap between plots.

The experimental area was ploughed on 19 April 2018 to a depth of 25 cm. Tined cultivation roto-ridging with a Rumptstad rototiller was carried out on 20 April. The experiment was planted by hand into the pre-formed ridges with Maris Piper seed (30 40 mm, tuber count 1714/50kg) on 25 April. The within-row plant spacing was 30 cm giving an intended plant population of

44 400/ha. Ammonium nitrate was applied at a rate of 200 kg N/ha post-planting, but pre-emergence, on 17 May. Herbicides and fungicides were applied as required to maintain the experiment free from weeds and blight.

4.3.1.2. Measurement cover crop and soil moisture

The growth and nutrient uptake of the cover crop was measured at periodic intervals during the spring on 9 March, 22 March, and 16 April. A 1 m^2 area of the cover crop was cut at ground level using scissors and then dried in a recirculating-air drying oven at 90 °C for 48 hours. The dried samples were sent to a commercial laboratory (NRM Ltd) for measurement of total N.

To assess the effect of cover crop on soil drying, soil water content was measured on 23 March, 16 and 19 April using a Delta-T Devices ML2 Theta Probe and HH2 reader. A small pit was dug with a spade in each plot and the water content measured in the top 5 cm and at 15 and 30 cm depth. On 19 April, a soil sample was taken at 0-10 cm depth using a 20 x 10 x 10 cm corer in all plots. The fresh weight was recorded, and 50 g of soil extracted for wet-sieving analysis using an Eijkelkamp Wet Sieving apparatus. The remaining bulk sample was then dried in a recirculating-air drying oven at 105 °C for 24 hours to determine dry bulk density.

4.3.1.3. Emergence, ground cover development and yield of the potato crop

Plant emergence was monitored by counting the number of emerged plants in the middle two rows of each plot every 3-4 days until emergence was complete. Ground cover (GC) was measured weekly using a grid from *c*. 50 % plant emergence until the canopies had senesced in the autumn. Integrated ground cover was estimated by calculating daily values of GC by interpolating between the weekly measurements and then summing these values. A single harvest of 2.25 m^2 was taken from rows three and four of the six-row plot on 1 October to measure yield, leaving discard areas at each end. The number of plants and mainstems was recorded and all tubers > 10 mm were retained for grading. The tubers were graded in 10 mm increments and the number and weight of tubers in each grade was recorded. A representative sub-sample (*c.* 1 kg) was taken from the grades with the largest yield (50-60 and 60-70 mm). This sub-sample was washed and chipped and then dried in a recirculating-air drying oven at 90 C for 48 hours to measure tuber DM concentration.

Irrigation was scheduled using the CUF Potato Irrigation Scheduling Model based on meteorological data obtained from a Delta-T Devices weather station *c*. 450 m from the experiment. The irrigation was carried out using a diesel engine-driven Briggs VR4 90/400 hosereel and R50 boom equipped with Senninger LDN UP3 Single Pad nozzle dropper pipes to allow discrete irrigation between plots. The SMD was maintained less than 25 mm and a total of 259 mm of irrigation was applied. There was 102 mm of rainfall between emergence and final harvest.

Data were analysed using analysis of variance with Genstat™ and treatment difference are only stated as significantly different if the probability of the differences occurring by chance was < 5 % ($P < 0.05$).

4.3.2. Results and Discussion

4.3.2.1. Cover crop growth and soil properties

The cover crop grew slowly in the cold weather during March and April. Consequently, the above-ground accumulation of DM and total N uptake between 9 March 16 April was small (Table 16).

Table 16. Dry matter yield and N content of cover crop on three dates in experiment 2018-32

Date	DM (t/ha)	Total N uptake (kg/ha)
9 March	0.96 ± 0.296	22.9 ± 7.64
22 March	1.13 ± 0.171	34.2 ± 7.12
16 April	2.16 ± 0.298	57.3 ± 14.62

Soil water content changed only slowly over the month before ploughing. On 23 March, bare soil was drier in the top 5 cm than where a cover crop was growing or where there was a mulch having been desiccated on 9 March (Table 17). There was no effect of cover crop on soil water content at the two deeper depths. Following rain and low evaporative drying in April, the soil surface wet up, but was still drier in bare soil than where a cover crop was planted (Table 17). Soils did not dry at all below 15 cm during April, despite having a cover crop with roots down to 25 cm depth.

Table 17. Effect of cover crop regime, depth and time of sampling on soil water content (% volumetric) in experiment 2018-32

		Depth		
Date	Treatment	Surface	15 cm	30 cm
23 March	No cover crop	19.2	28.2	27.4
	Defoliated	22.7	28.5	28.2
	Undefoliated	23.3	28.6	28.3
S.E. (14 D.F.)		0.63	0.52	0.47
16 April	No cover crop	24.5	29.4	29.2
	Defoliated	26.3	30.5	28.4
	Undefoliated	29.9	30.7	29.7
S.E. (14 D.F.)		0.72	0.53	0.36
19 April	No cover crop	22.2	30.1	27.4
	Defoliated	24.6	29.3	28.1
	Undefoliated	25.9	29.4	27.9
S.E. (14 D.F.)		0.55	0.50	0.46

Soil bulk density in the top 10 cm of the profile was significantly lower on 9 March where a cover crop had been grown (1.27 ± 0.018g/cm^3) than where the cover crop was desiccated at emergence (1.34 g/cm^3). The soil structure was also very different in terms of friability, with the cover cropped soil having a VESS Score of 2.5 and the no cover crop treatment a Score of 3.5 (Figure 5). This VESS system (Ball *et al.* 2012) of scoring will be extended in the 2019 cover crop experiment by sampling on a more frequent basis during the winter and spring.

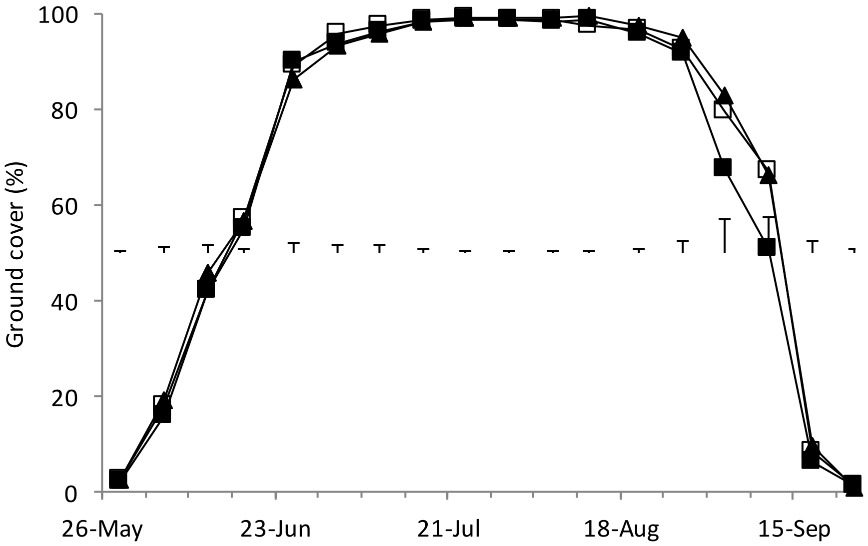
Figure 5. Visual soil structure on 9 March. *a)* undefoliated cover crop; *b)* no cover crop.

(a) *(b)*

4.3.2.2. *Emergence and ground cover development of the potato crop*

First emergence was noted on 22 May (27 days after planting (DAP)) and 50 % emergence was recorded on 26 May (31 DAP). All plots reached > 95 % emergence by 4 June and there were no effects of cover crop treatments on emergence. The effect of cover crop treatments on the pattern of season-long GC development is shown in Figure 6. There were no significant effects of cover crop management on rate of increase or longevity of ground cover and the overall mean ground cover duration was *c*. 8600 % days.

Figure 6. Effect of cover crop treatments on ground cover development. No cover crop, ■; cover crop defoliated on 9 March, □; cover crop undefoliated, ▲. Error bars based on 14 D.F.



4.3.2.3. Yield and crop quality at final harvest on 1 October

At final harvest there was no effect of the treatments on either plant or mainstem populations which averaged 44400 and 113900/ha, respectively. There was no effect of cover crop treatments on the total number of tubers (Table 18). Defoliating the cover crop on 9 March (41 days before ploughing) reduced both total and > 40 mm yield compared with no cover crop and an undefoliated cover crop (Table 18). The tuber DM concentration of the defoliated cover crop treatment was high and combined with the FW yields, resulted in there being no significant difference in DM yield between cover crop treatments, although the same trend was apparent between the defoliated cover crop and the other two treatments as for FW yields (Table 18).

Table 18. Main effects of compost and N applications at NIAB on components of yield and dry matter concentration (Expt 2018-32)

Treatment	Total no. of tubers (000/ha)	Tuber FW yield (t/ha)	Yield > 40 mm (t/ha	Tuber DM concentration (%)	Tuber DW yield (t/ha)
No cover crop	609	55.7	50.0	26.2	14.6
Cover crop defoliated	582	50.4	44.7	26.7	13.5
Cover crop undefoliated	600	55.9	50.6	26.1	14.6
S.E. (14 D.F.)	13.5	1.54	1.54	0.27	0.37

4.4. Replicated Experiment at NIAB F30 with compost (2019-49)

4.4.1. Materials & Methods

4.4.1.1. Soils, location, cultivations and experimental design

Experiment 2019-49 was conducted in F30 at NIAB, Cambridge (52.2371 °N, 0.0992 °E) on a sandy loam soil (62 % sand, 25 % silt and 13 % clay) with 8-20 % stone, 3.3 % organic matter content and a pH of 7.7. The P, K and Mg Indices were 2, 1.5 and 2, respectively. On 4 March, 250 kg K_2O/ha was applied across the whole field. The field was subsoiled on 8 September 2018 and drilled with a cover crop of winter oats on 15 September. The cover crop was sprayed with glyphosate on 29 March and mowed to a height of 10-12 cm using a tractor-mounted mower on 30 March. The area was ploughed on 1 April.

The experiment tested two compaction regimes (Uncompacted; Compacted), two irrigation regimes (Dry; Wet) and two rates of compost application (0; 30 t/ha) in factorial combination. Each treatment combination was replicated three times and allocated at random to blocks. Each plot was 4.5 m long by six rows (4.5 m) wide. There was an extra discard row between plots and a 1 m gap between plots as an irrigation guard. Harvests and other measurements were conducted on the middle four rows of each plot.

The soil was just below field capacity at plough depth at this stage. Post-ploughing on 1 April, the experimental area was roto-ridged on 4 April with a Rumptstad rototiller attached to a John Deere 6630 tractor. All of the ridges in the experimental area were levelled using a Kuhn HR4001 power harrow with PK2 packer roller attached to a John Deere 6120R tractor. The tractor ran on Firestone 460/85/R38 rear tyres at 11 PSI pressure and 420/85/R24 front tyres at the same pressure. The compaction treatments were carried immediately afterwards by driving the same John Deere 6120R tractor with rear-mounted Kuhn HR4001 power harrow with PK2 packer roller but with 1000 kg front weight (total laden weight 8950 kg). The front and rear tyres were pumped up to 22 PSI pressure. The tractor was driven over the entire area of the plot, so that by driving and reversing across the plot, each tyre compressed the soil twice. Using the Terranimo soil compaction model (www.terranimo.uk) this would be expected to result in major soil compaction to 40 cm depth and minor compaction to 55 cm given the weight of tractor and implements, soil water content and bulk density at the time of compaction. Following the compaction treatments being imposed, the entire experimental area was roto-ridged on 4 April with a Rumptstad rototiller attached to a John Deere 6630 tractor.

The two irrigation treatments were Dry, irrigated whenever the SMD reached 60 mm and Wet, irrigated whenever the SMD reached 25 mm. Application amounts varied from 20-22 mm in the Dry treatment (two irrigations totalling 42 mm) and from 17-22 mm in the Wet treatment (10 irrigations totalling 198 mm). Irrigation was scheduled using the CUF Potato Irrigation Scheduling Model based on meteorological data obtained from a Delta-T Devices weather station *c.* 450 m from the experiment. The two irrigation treatments were timed based on the mean SMD within each irrigation treatment combination. The irrigation was carried out using a diesel engine-driven Briggs VR4 90/400 hosereel and R50 boom equipped with Senninger LDN UP3 Single Pad nozzle dropper pipes to allow discrete irrigation between plots.

The compost treatments were applied by hand on 1 April onto the mown oat cover crop and incorporated by ploughing on the same day. At the application rate of 30 t/ha, the compost supplied 16.5 ± 1.89 t/ha of DM, 372 ± 17.1 kg total N/ha, 81 ± 1.87 kg total P/ha, 226 ± 16.3 kg total K/ha and 6.1 ± 0.97 t total C/ha. The C : N ratio was *c.* 16, so relatively little N would be available to the potato crop.

The experiment was planted by hand into the pre-formed ridges with Maris Piper seed (30 40 mm, tuber count 1639/50 kg) on 5 April. The within-row plant spacing was 30 cm giving an intended plant population of 44 400/ha. Ammonium nitrate was applied at a rate of 200 kg N/ha post-planting, but pre-emergence, on 30 April. Herbicides and fungicides were applied as required to maintain the experiment free from weeds and blight.

4.4.1.2. Measuring emergence, ground cover and yield in the potato crop

Plant emergence was monitored by counting the number of emerged plants in the middle two rows of each plot every 3–4 days until emergence was complete. Ground cover (GC) was measured weekly using a grid from *c.* 50 % plant emergence until the canopies had senesced in the autumn. Integrated ground cover was estimated by calculating daily values of GC by interpolating between the weekly measurements and then summing these values. Radiation absorption was calculated by assuming that daily absorbed radiation was the product of incident radiation and fractional ground cover and then summing. A single harvest was taken on 3 October to measure yield. At harvest, 10 plants were taken from rows three and four of the six-row plot, leaving discard areas at each end. The number of plants and mainstems was recorded and all tubers > 10 mm were retained for grading. The tubers were graded in 10 mm increments and the number and weight of tubers in each grade was recorded. A representative sub-sample (*c*. 1 kg) was taken from the grades with the largest yield (50-60 and 60-70 mm). This sub-sample was washed and chipped and then dried in a recirculating-air drying oven at 90 °C for 48 hours to measure tuber DM concentration.

4.4.1.3. Soil sampling

During the season, triplicate soil cores (55 mm diameter x 40 mm cylinders) were taken at 25 cm depth below the centre of the ridge. One core was stored at 3 °C and assessed for root length density at a later stage, another core had the soil extracted and dried in a recirculating-air drying oven at 105 °C for 24 hours to determine bulk density and the third core was sent to James Hutton Institute for laboratory measurements of soil water release and strength using a pressure table and micro-penetrometer.

4.4.2. Results and Discussion

4.4.2.1. Emergence and ground cover development

First emergence was noted on 10 May (35 days after planting (DAP)). Mean date of 50 % emergence was 15 May (40 DAP). Neither compaction nor compost affected the date of 50 % emergence or final emergence (which averaged 99.6 % of that intended). The effect of the treatments on the pattern of season-long ground cover development is shown in Figure 7 and on season-long integrated GC and radiation absorption in Table 19. Compaction, unlike 2018, had no significant effect on GC development or persistence, and the season-long integrated GC was similar for both compaction regimes (8479 % days, Figure 7b, Table 19). Full irrigation maintained GC following a very hot period in late July, which caused a significant loss of GC where the SMD was allowed to increase to 60 mm (Figure 8a). The overall effect of irrigation regime on ground cover duration and light interception was equivalent to 11 days at full ground cover (Table 19). Adding compost had no significant effect on GC (Figure 7c, Table 19). Radiation absorption followed the same patterns as GC (Table 19).

Figure 7. Effect of *(a)* irrigation applications, *(b)* compaction and *(c)* compost application on ground cover development in experiment 2019-49. Uncompacted, Unirrigated, No compost ■; Compacted, Irrigated, Compost, □. Error bars based on 21 D.F.

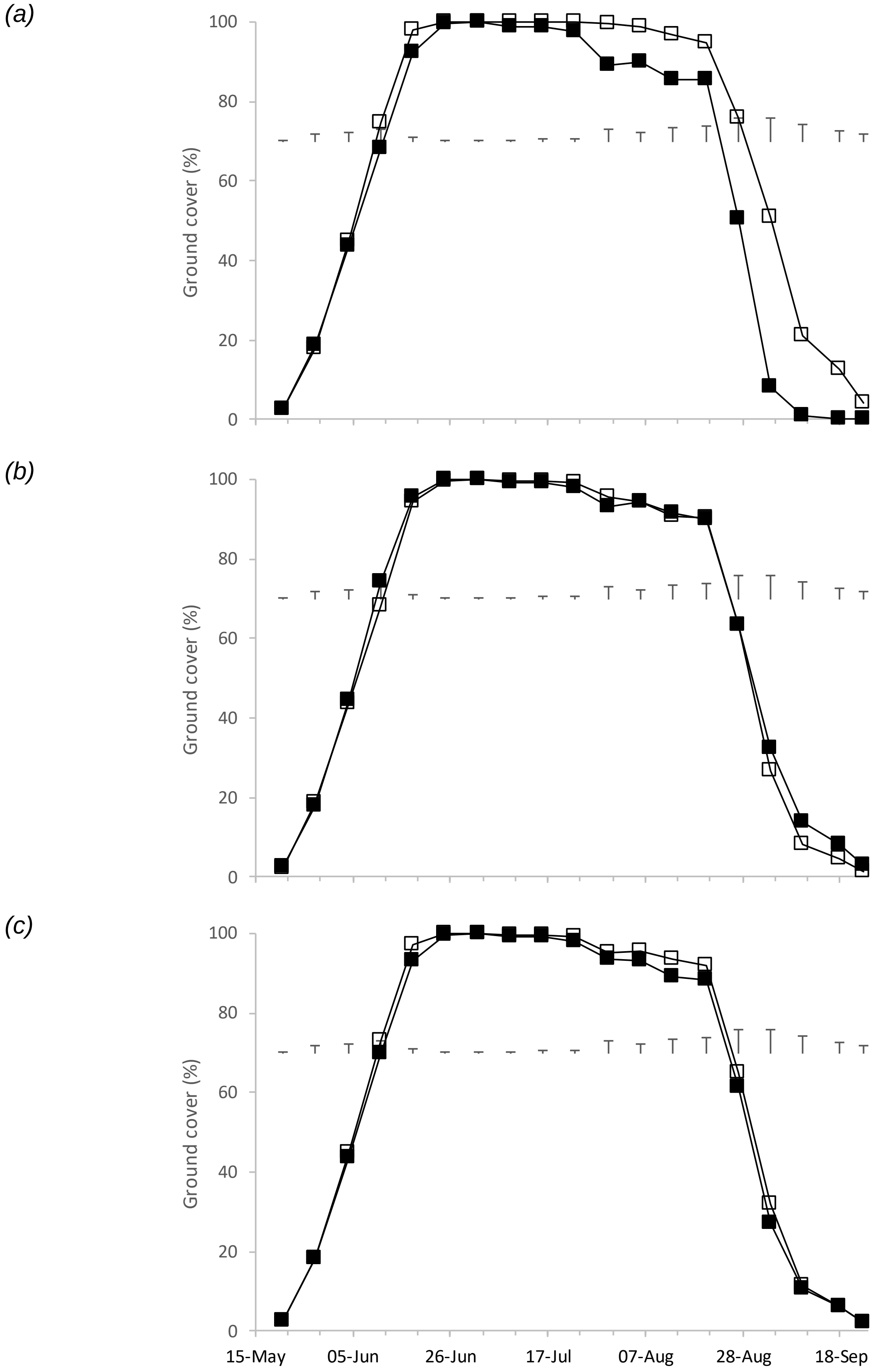


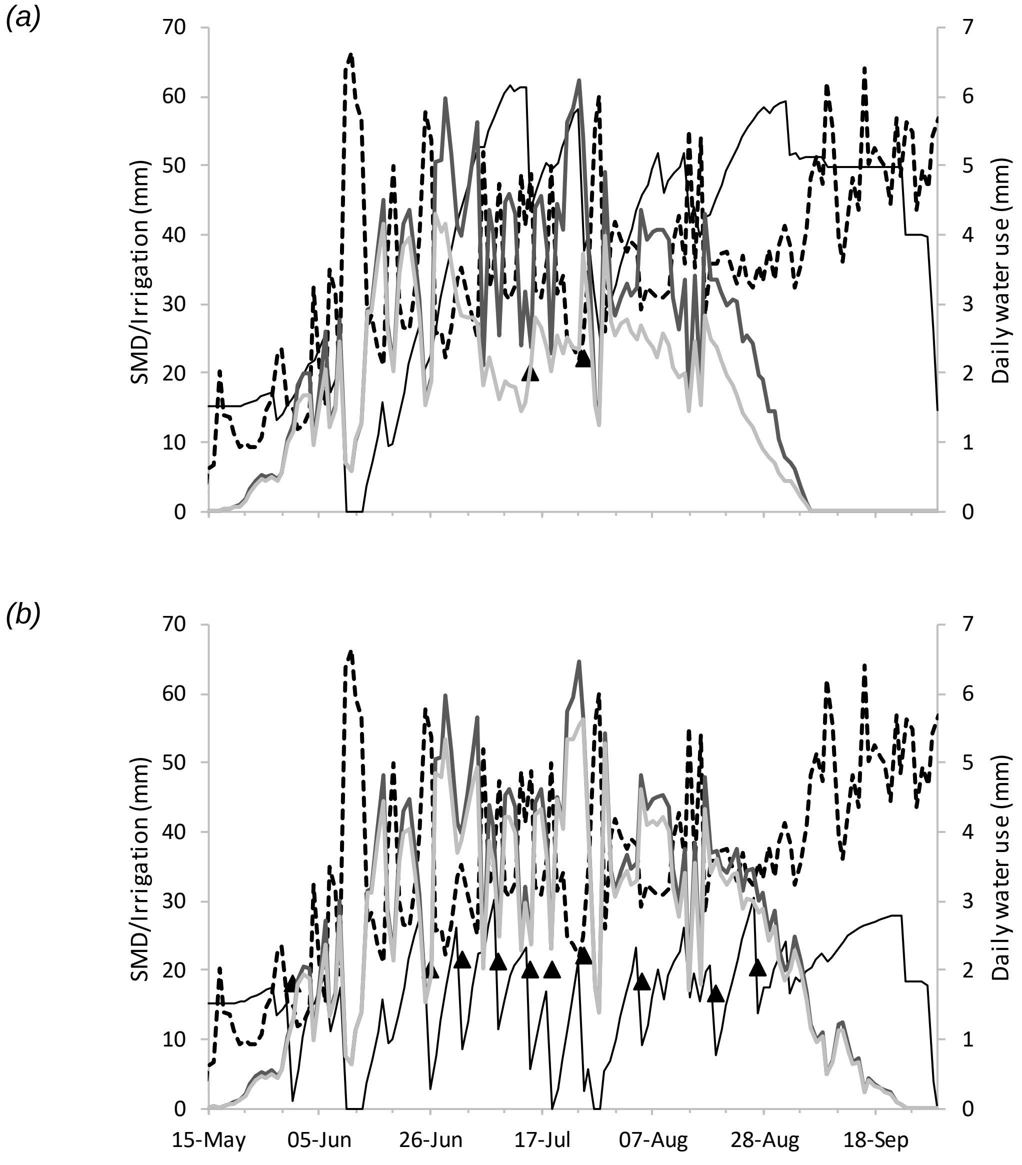
Table 19. Main effects of compaction, irrigation and compost treatments on season-long integrated ground cover and radiation absorption in experiment 2019-49

Treatment	Integrated ground cover (% days)	Radiation absorption (TJ/ha)	Radiation use efficiency (TJ/t tuber DM)
Dry	7910	13.83	0.853
Wet	9047	15.56	0.924
Uncompacted	8550	14.79	0.810
Compacted	8407	14.61	0.967
No compost	8368	14.52	0.902
Compost	8589	14.87	0.875
S.E. (21 D.F.)	167.3	0.251	0.0362

4.4.2.2. Soil moisture deficits and daily water use

June 2019 was characterised by larger than average ET and a week of rainfall totalling 57 mm starting 7 June. This reduced the SMD to zero in all treatments. The above-average ET demand on the crops continued throughout July and SMD in the Dry treatment reached the trigger deficit of 60 mm on 10 July (Figure 8). Temperatures peaked at 39.3 C on July, and the Dry treatment received its second (and last irrigation) on this day. August turned duller and cooler, but ET was still greater than average. Wet treatments were generally maintained < 25 mm SMD but peaked at 30 mm on 8 July (Figure 8).

Figure 8. Modelled soil moisture deficits, daily water use and irrigation in experiment 2019-49. *(a)* Dry; *(b)* Wet. Data are means of both compaction and both compost treatments. Soil moisture deficit, ——; limiting soil moisture deficit, ▪▪▪▪; irrigation, ▲; potential daily water use, ▬; actual daily water use, ▬.



4.4.2.3. *Yield and crop quality at final harvest on 3 October*

At final harvest, there was no effect of the treatments on either plant or mainstem populations which averaged 44400 and 119500/ha, respectively. The total number of tubers was also unaffected by treatment (Table 20). Total yield, yield > 40 mm and tuber DM yield were all increased with frequent irrigation compared with infrequent and, surprisingly, having compacted soils rather than uncompacted (Table 20). Frequent irrigation on average increased total FW yield by 18.6 t/ha compared with infrequent, whilst compaction increased total yield by 3.6 t/ha, albeit the effect was only just significant (P = 0.050). The effect of a similar irrigation regime in 2018 was smaller with irrigation (15.6 t/ha) than in 2019. Compaction reduced yield by 5.6 t/ha in 2018. Compost application did not affect yield in 2019. Tuber DM concentration was 1 % higher where irrigation was infrequently applied (Table 20). There was no effect of compaction or compost on tuber DM concentration (Table 20).

The canopies were dead at final harvest, but there would have been some DM in the dead haulm that would not be accounted for in calculating radiation use efficiency (RUE). Looking purely at RUE of tuber DM, frequent irrigation increased RUE compared with higher deficit irrigation (Table 19). Compaction increased RUE, possibly as a consequence of making the canopies shorter and slightly more determinate and increasing the harvest index (Table 19), but the effect was not as great as observed in 2018. Compost amendment had no effect on RUE.

Table 20. Factorial and main effects of irrigation, ii and compost on components of yield and dry matter concentration in experiment 2019-49

Irrigation	Compaction	Compost	Total no. of tubers (000/ha)	Tuber FW yield (t/ha)	Yield > 40 mm (t/ha)	Tuber [DM] (%)	Tuber DW yield (t/ha)
Dry	Uncompacted.	None	500	46.8	42.8	23.7	11.1
		Compost	461	44.0	40.1	24.0	10.6
	Compacted	None	479	47.6	44.3	24.4	11.6
		Compost	490	49.0	46.0	23.6	11.6
Wet	Uncompacted.	None	500	62.9	61.2	23.4	14.7
		Compost	434	63.9	62.1	22.2	14.3
	Compacted	None	501	64.8	62.2	23.5	15.2
		Compost	491	70.5	68.8	22.6	16.0
S.E. (21 D.F.)			27.6	2.44	2.58	0.52	0.73
Dry			482	46.9	43.3	23.9	11.2
Wet			481	65.5	63.6	22.9	15.0
	Uncompacted.		474	54.4	51.5	23.3	12.7
	Compacted		490	58.0	55.3	23.5	13.6
		None	495	55.5	52.6	23.7	13.2
		Compost	469	56.9	54.2	23.1	13.1
S.E. (21 D.F.)			13.78	1.22	1.29	0.26	0.37

This experiment has demonstrated the very significant effects of irrigation on ground cover development and longevity, light interception and yield in a dry, hot season. Compaction actually increased yield compared with uncompacted soil, the opposite to expectations and the results from the experiment in 2018. Soil bulk density at ploughing was lower in 2019 (1.16 g/cm^3) than in 2018 (1.27 g/cm^3), which may have made it hard to compact soil as thoroughly as in 2018. The soil water content at plough depth was 24 % in 2019 versus 28 % in 2018, which would also have reduced the effects of trafficking in 2019. The addition of compost in 2018 and 2019 did not confer any immediate resistance to reducing the effects of compaction.

This experiment also forms part of Katharina Huntenberg's PhD at Lancaster University (AHDB Project Reference 11140035) and over the course of the 2019 summer she took several more limited measurements on soil resistance and leaf water potential than in 2018. It is hoped that this suite of measurements from 2018 and 2019 will be able to explain some of the signalling involved in plant stresses triggered by compaction and dry soil.

4.5. Replicated Experiment at NIAB F30 with cover crops (2019-50)

4.5.1. Materials and Methods

4.5.1.1. Soils, location, cultivations, and experimental design

Experiment 2019-50 was conducted in F30 at NIAB, Cambridge (52.2371 °N, 0.0992 °E) on a sandy loam soil (62 % sand, 25 % silt and 13 % clay) with 8-20 % stone, 3.3 % organic matter content and a pH of 7.7. The P, K and Mg Indices were 2, 1.5 and 2, respectively. On 4 March, 250 kg K_2O/ha was applied across the whole field. The field was subsoiled on 8 September 2018 and drilled with a cover crop of winter oats at a seed rate of 70 kg/ha on 15 September. The area was ploughed on 1 April. No fertilizer was applied to the cover crop to aid its establishment. The experiment tested three cover crop management regimes: no cover crop (cover crop sprayed out with glyphosate on 19 October 2018 (10 days after emergence) using a knapsack sprayer); cover crop allowed to grow until 21 March 2019 and then sprayed off; cover crop left growing until ploughing. Each treatment combination was replicated eight times and allocated at random to blocks. Each plot was 6 m long by six rows (4.5 m) wide. There was a 1 m access gap between plots.

The experimental area was ploughed on 1 April 2019 to a depth of 25 cm. Roto-ridging with a Rumptstad rototiller was carried out on 1 April. The experiment was planted by hand into the pre-formed ridges with Maris Piper seed (30-40 mm, tuber count 1639/50kg) on 5 April. The within-row plant spacing was 30 cm giving an intended plant population of 44400/ha. Ammonium nitrate was applied at a rate of 200 kg N/ha post-planting, but pre-emergence, on 30 April. Herbicides and fungicides were applied as required to maintain the experiment free from weeds and blight.

Irrigation was scheduled using the CUF Potato Irrigation Scheduling Model based on meteorological data obtained from a Delta-T Devices weather station *c*. 450 m from the experiment. The irrigation was carried out using a diesel engine-driven Briggs VR4 90/400 hosereel and R50 boom equipped with Senninger LDN UP3 Single Pad nozzle dropper pipes to allow discrete irrigation between plots. The SMD was maintained less than 25 mm and a total of 202 mm of irrigation was applied. There was 222 mm of rainfall between emergence and final harvest.

4.5.1.2. Measurements on the cover crop, soil moisture and physical properties

The growth and nutrient uptake of the cover crop was measured on 28 March. A 1 m^2 area of the cover crop was cut at ground level using scissors and then dried in a recirculating-air drying oven at 90 °C for 48 hours. The dried samples were sent to a commercial laboratory (NRM Ltd) for measurement of total N.

To assess the effect of cover crop on soil drying, soil water content was measured on 21 and 29 March and 1 April using a Delta-T Devices ML2 Theta Probe and HH2 reader. A small pit was dug with a spade in each plot and the water content measured in the top 5 cm and at 15 and 30 cm depth. On 29 March, a soil sample was taken at 0-10 cm depth using a 20 x10 x 10 cm corer in all plots. The fresh weight was recorded, and 50 g of soil extracted for wet-sieving analysis using an Eijkelkamp Wet Sieving apparatus. The remaining bulk sample was then dried in a recirculating-air drying oven at 105 °C for 24 hours to determine dry bulk density. Soil structure was evaluated using the Visual Evaluation of Soil Structure (VESS) scoring system (Ball *et al*. 2012) on 20 December 2018, 16 January, 25 February, 21 March and 29 March

2019. A spade was used to extract a 25 x 25 x 25 cm cube of soil and the VESS score estimated by placing the cube on a plastic sheet prior to assessment.

4.5.1.3. Emergence, ground cover and yield in the potato crop

Plant emergence was monitored by counting the number of emerged plants in the middle two rows of each plot every 3-4 days until emergence was complete. Ground cover was measured weekly using a grid from *c*. 50 % plant emergence until the canopies had senesced in the autumn. Integrated ground cover was estimated by calculating daily values of GC by interpolating between the weekly measurements and then summing these values. A single harvest of 2.25 m^2 was taken from rows three and four of the six-row plot on 7 October to measure yield, leaving discard areas at each end. The number of plants and mainstems was recorded and all tubers > 10 mm were retained for grading. The tubers were graded in 10 mm increments and the number and weight of tubers in each grade was recorded. A representative sub-sample (*c*. 1 kg) was taken from the grades with the largest yield (50-60 and 60-70 mm). This sub-sample was washed and chipped and then dried in a recirculating-air drying oven at 90 °C for 48 hours to measure tuber DM concentration.

4.5.2. Result and Discussion

4.5.2.1. Cover crop growth and soil properties

The cover crop grew much more quickly and for longer than in autumn/winter 2017/2018. The crop was *c.* 40 cm tall in spring 2019 compared to *c*. 20 cm in 2018. The above-ground accumulation of DM and total N uptake of the undefoliated crop was nearly four times greater and 2.3 times greater, respectively, in 2019 than at the equivalent time in 2018 (Table 21).

Table 21. Dry matter yield and N content of cover crop at ploughing in experiments 2018-32 and 2019-50

Date	DM (t/ha)	Total N uptake (kg/ha)
16 April 2018	2.16 ± 0.298	57.3 ± 14.62
28 March 2019	8.17 ± 1.662	133.1 ± 28.49

Soil water content changed only slowly over the month before ploughing. On 21 March, bare soil was drier in the top 5 cm than where a cover crop was growing (Table 22). There was no effect of cover crop on soil water content at intended plough depth. By 29 March, all treatments were beginning to dry at 30 cm depth, most probably owing to drainage (Table 22), but bare soil was drier in the top 5 cm than where a cover crop was growing, or a mulch remained. On the day of ploughing, the undefoliated cover crop had begun significantly to dry the profile at 30 cm, but the surface remained wetter than where no cover crop was grown owing to reduced evaporation from the soil protected by the cover crop (Table 22). The cover crop desiccated on 21 March did not dry the soil at 30 cm following spraying and actually prevented moisture loss from the surface horizon, meaning that soil was wet both at plough depth and on the surface (Table 22).

Table 22. Effect of cover crop regime, depth and time of sampling on soil water content (% volumetric) in experiment 2019-50

		Depth	
Date	Treatment	Surface	30 cm
21 March	No cover crop	23.9	28.4
	Defoliated	30.8	29.6
	Undefoliated	31.0	30.0
S.E. (14 D.F.)		0.52	0.59
29 March	No cover crop	20.2	26.8
	Defoliated	25.6	27.6
	Undefoliated	23.9	25.4
S.E. (14 D.F.)		0.56	0.77
1 April	No cover crop	18.6	26.9
	Defoliated	24.3	26.7
	Undefoliated	22.4	23.7
S.E. (14 D.F.)		0.43	0.50

Soil bulk density in the top 10 cm of the profile was slightly (but not statistically) lower on 28 March where a cover crop had been grown (1.16 ± 0.020g/cm^3) than where no cover crop grew over winter (1.20 g/cm^3). However, the mean bulk density was much lower (1.18 g/cm^3) in 2019 than in 2018 (1.31 g/cm^3), perhaps indicating better soil quality. The soil structure was different in terms of friability, with the cover cropped soil surprisingly having a numerically worse VESS Score (less friable) throughout the winter than no cover crop (Table 23), but on some occasions the differences were not significant. Overall, the VESS Score was poorer under the cover crop in 2019 than in 2018 (2.5), where there was much more benefit of growing a cover crop than having bare soil (3.5). As mentioned previously, the soil water content was higher throughout the spring under cover-cropped than under bare soil, and this seemed to reduce soil weathering.

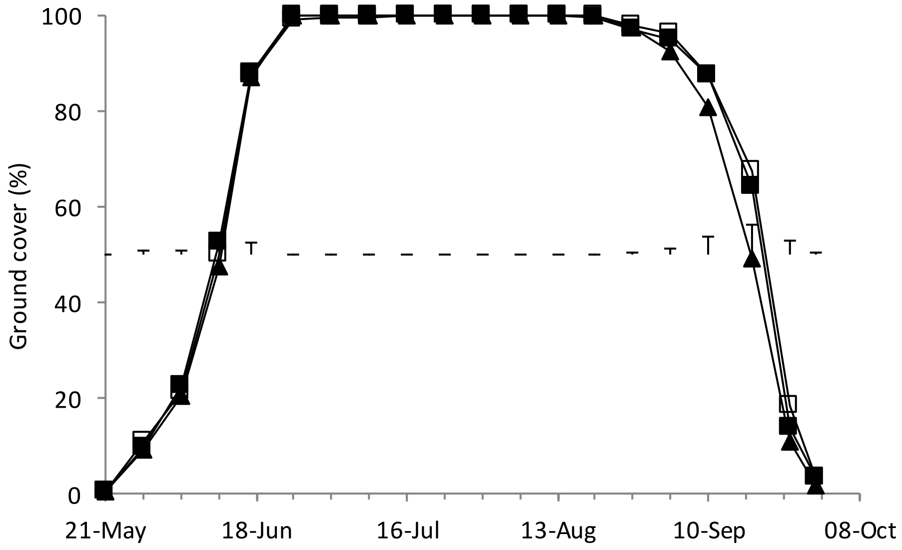
Table 23. VESS Scores on selected dates throughout winter 2018 and spring 2019 in experiment 2019-50

Treatment	20 December	16 January	25 February	21 March	29 March
No cover crop	3.50	3.25	3.25	3.13	2.88
Defoliated	-	-	-	3.41	3.25
Undefoliated	3.75	3.88	3.63	3.50	3.38
S.E.	0.222	0.129	0.186	0.129	0.142
D.F.	7	7	7	14	14

4.5.2.2. *Emergence and ground cover development*

First emergence was noted on 14 May (39DAP) and 50 % emergence was recorded on 18 May (41 DAP). All plots reached > 99 % of their intended population by 28 May and there were no effects of cover crop treatments emergence. The effect of cover crop treatments on the pattern of season-long GC development is shown in Figure 9. There were no significant effects of cover crop management on rate of increase or longevity of ground cover and the overall mean ground cover duration was *c*. 9970 % days.

Figure 9. Effect of cover crop treatments on ground cover development in experiment 2019-50. No cover crop, ■; cover crop defoliated on 21 March, □; cover crop undefoliated, ▲. Error bars based on 14 D.F.



4.5.2.3. *Yield and crop quality at final harvest on 7 October*

At final harvest there was no effect of the treatments on either plant or mainstem populations which averaged 44400 and 119000/ha, respectively, and there was no effect of cover crop treatment on the total number of tubers (Table 24). Leaving the cover crop to grow on until ploughing resulted in a numerically, but not statistically, greater total, > 40 mm and tuber DM yield compared with no cover crop and a cover crop defoliated 12 days before ploughing (Table 24). These data support the findings in the AHDB Rotations Project reported elsewhere (Tuber DM concentration was unaffected by cover crop treatment (Table 24).

Table 24. Main effects of compost and N applications on components of yield and dry matter concentration in experiment 2019-50

Treatment	Total no. of tubers (000/ha)	Tuber FW yield (t/ha)	Yield > 40 mm (t/ha	Tuber DM concentration (%)	Tuber DW yield (t/ha)
No cover crop	467	66.1	63.7	22.8	15.1
Cover crop defoliated	459	66.1	63.9	23.0	15.2
Cover crop undefoliated	455	69.6	67.4	22.3	15.6
S.E. (14 D.F.)	22.0	1.80	1.86	0.37	0.47

The main hypothesis behind the experiment was that an actively growing cover crop would be able to dry the soil at cultivation depth, leading to an improved window for ploughing in spring compared with a bare stubble or cultivated soil surface. In fact, the opposite happened in that the cover crop (both undefoliated and desiccated) acted as a surface mulch preventing the drying of the top 5 cm of soil. February was dry, but there were 35 mm of rain from 1st to 15th March and this refilled the profile down to 30 cm. Despite the much more vigorous and profuse cover crop canopy in 2019 compared to 2018, soil drying under the cover crop at plough depth (*c.* 30 cm) did not begin until late March and it would have been useful to delay the ploughing a further 7-10 days to measure the consequences. Plans for 2020 will include treatments designed to investigate this.

4.6. Replicated Experiment at NIAB F38/39 with cover crops (2020-74)

4.6.1. Materials and Methods

4.6.1.1. Soils, location and experimental design

The cover crop experiment was conducted in F38 at NIAB, Cambridge (52.2422 °N, 0.0988 °E) on a sandy loam soil (74 % sand, 17 % silt and 9 % clay) with 8-20 % stone, 2.7 % organic matter content and a pH of 7.4. The P, K and Mg Indices were 2+, 2+ and 2, respectively. The entire field was subsoiled on 8 September 2019 and drilled with a cover crop of winter oats at a seed rate of 70 kg/ha on 11 September. No fertilizer was applied to the cover crop at drilling. The experimental plot layout was marked out in February 2020 and the treatments imposed on the growing cover crop. The experiment tested three cover crop management regimes: cover crop sprayed out with glyphosate on 18 March 2020 using a knapsack sprayer (Early Defoliation); cover crop allowed to grow until 15 April 2020 and then sprayed off (Late Defoliation); cover crop left growing until primary cultivation (Undefoliated). Each treatment combination was replicated eight times and allocated at random to blocks. Each plot was 6 m long by six rows (4.5 m) wide. There was a 1 m access gap between plots.

The experimental area was cultivated with a Kuhn Cultimer combination cultivator pulled by a John Deere 6195R tractor at 8:30 h on 23 April to a depth of 15 cm and then repeated to a depth of 25 cm 4 hours later. Roto-ridging with a Rumptstad rototiller was carried out in the afternoon of 23 April. Irrigation was scheduled using the NIAB CUF Potato Irrigation Scheduling Model based on meteorological data obtained from a Delta-T Devices weather station *c*. 450 m from the experiment. The mean ground cover was used to calculate Kc (crop coefficient). The irrigation was carried out using a diesel engine-driven Briggs VR4 90/400 hosereel and R50 boom equipped with Senninger LDN UP3 Single Pad nozzle dropper pipes to allow discrete irrigation between plots. The crop was maintained at a soil moisture deficit of < 25 mm using a total of 251 mm of irrigation. There was 197 mm of rainfall between emergence and final harvest.

On 4 March, 250 kg K_2O/ha was applied across the experiment on top of the cover crop. Ammonium nitrate was applied at a rate of 200 kg N/ha post-planting, but pre-emergence, on 30 April. Herbicides and fungicides were applied as required to maintain the experiment free from weeds and blight.

The experiment was planted by hand into the pre-formed ridges with 35-40 mm Maris Piper SE2 seed (tuber count 1 467/50 kg) on 24 April. The within-row plant spacing was 30 cm giving an intended plant population of 44 400/ha.

4.6.1.2. Measurement of the cover crop, soil moisture and soil structure

The growth and nitrogen uptake of the cover crop was measured on 25 March. A 1 m^2 area of the cover crop was cut at ground level using scissors and then dried in a recirculating-air drying oven at 90 °C for 48 hours. The dried samples were sent to a commercial laboratory (NRM Ltd) for measurement of total N. To assess the effect of cover crop on soil drying, soil water content was measured on 21 April using a Delta-T Devices ML2 Theta Probe and HH2 reader. A small pit was dug with a spade in each plot and the water content measured in the top 5 cm and at 15 and 30 cm depth. On 24 March, a soil sample was taken at 0-10 cm depth using a 20 x 10 x 10 cm corer in all plots. The fresh weight was recorded, and 50 g of soil extracted for wet-sieving analysis using an Eijkelkamp Wet Sieving apparatus. The remaining bulk sample was then dried in a recirculating-air drying oven at 105 °C for 24 hours to determine dry bulk density. Soil structure was evaluated using the Visual Evaluation of Soil Structure (VESS) scoring system (Ball *et al*. 2012) on 25 February, 24 March and 21 April 2020. A spade was used to extract a 25 x 25 x 25 cm cube of soil and the VESS score estimated by placing the cube on a plastic sheet for examination and photographing.

4.6.1.3. Emergence Ground cover and yield in the potato crop

Plant emergence was monitored by counting the number of emerged plants in the middle two rows of each plot every 3-4 days until emergence was complete. Ground cover (GC) was measured weekly using a grid from c. 50 % plant emergence until the canopies had senesced in the autumn. Integrated ground cover was estimated by calculating daily values of GC by interpolating between the weekly measurements and then summing these values. Total radiation absorption was calculated from the interpolated daily GC and the daily radiation total. A single harvest of 2.25 m^2 was taken from rows three and four of the six-row plot on 29 September to measure yield, leaving discard areas at each end. The number of plants and mainstems was recorded and all tubers > 10 mm were retained for grading. The tubers were graded in 10 mm increments and the number and weight of tubers in each grade was recorded. A representative sub-sample (*c*. 1 kg) was taken from the grades with the largest yield (50-60 and 60-70 mm). This sub-sample was washed and chipped and then dried in a recirculating-air drying oven at 90 °C for 48 hours to measure tuber DM concentration.

Data were analysed using analysis of variance with Genstat. Error bars in figures are one S.E. in length.

4.6.2. Results and Discussion

4.6.2.1. Cover crop growth and soil properties

The cover crop grew quickly and was similar to 2019, and the crop was *c*. 30 cm tall in spring 2020 compared to *c*. 20 cm in 2018. The above-ground accumulation of DM was much lower than in 2019, however (Table 25), and total N uptake similar to 2018, but only 40 % of that achieved in 2019 (Table 25).

Table 25. Dry matter yield and N content of cover crop in spring in experiment 2018-32, 2019-50 and 2020-74

Date of sampling	DM (t/ha)	Total N uptake (kg/ha)
16 April 2018	2.16 ± 0.298	57 ± 14.6
28 March 2019	8.17 ± 1.662	133 ± 28.5
25 March 2020	2.88 ± 0.259	54 ± 4.5

From visual inspection, soil dried only slowly during March. When measured on 21 April, two days before primary cultivation, the surface soil layer had similar soil water content irrespective of cover crop treatment, but at 30 cm depth the Undefoliated and Late Defoliation cover crop treatments had dried the soil much more that the cover crop defoliated on 18 March (Table 26). This drying during April reduced soil water content well below field capacity (*c*. 23-24 %) and should have aided cultivating without damaging soil structure.

Table 26. Effect of cover crop regime and depth of sampling on soil water content (% volumetric) on 21 April in experiment 2020-74

		Depth	
Date	Treatment	Surface	30 cm
1 April	Undefoliated	13.6	15.9
	Early Defoliation	13.3	18.6
	Late Defoliation	14.0	14.7
S.E. (14 D.F.)		0.56	0.36

The soil structure improved slightly from February until March, but there was a much more dramatic improvement during April (Table 27). Numerically, Early Defoliation treatments had a poorer VESS Score than Undefoliated or Late Defoliation. Overall, the VESS Score by late April was better than in 2018 (2.5) and much better than in 2019 (3.4), but the final VESS assessment was performed 3 weeks later in 2020 than in the two previous years and benefitted from a longer period of soil drying.

Table 27. VESS Scores on selected dates in spring 2020 in experiment 2020-74

Treatment	25 February	24 March	21 April
Undefoliated	3.75	3.00	1.56
Early Defoliation	3.94	3.06	1.94
Late Defoliation	3.75	2.88	1.50
S.E. (14 D.F.)	0.133	0.173	0.132

4.6.2.2. Emergence and ground cover development

First emergence was noted on 19 May (39 days after planting (DAP)) and 50 % emergence in in the Early Defoliated treatment was recorded on 25 May (31 DAP), 3 days earlier that Undefoliated or Late Defoliated. All plots reached > 99 % of their intended plant population by 2 June and there were no effects of cover crop treatments on final emergence.

The effect of cover crop treatments on the pattern of season-long GC development is shown in Figure 10. The 3-day earlier emergence of the Early Defoliation cover crop treatment led to advanced GC development compared to Undefoliated or Late Defoliation treatments and this led to full GC being reached *c.* 5 days earlier. As a consequence of this earlier GC development and a similar commencement and rate of canopy senescence, the Early Defoliation treatment had a larger integrated GC and higher radiation absorption than Undefoliated or Late Defoliation treatments (Table 28).

Figure 10. Effect of cover crop treatments on ground cover development in experiment 2020-74. Undefoliated, ■; Early Defoliation, □; Late Defoliation, ▲. Error bars based on 14 D.F.

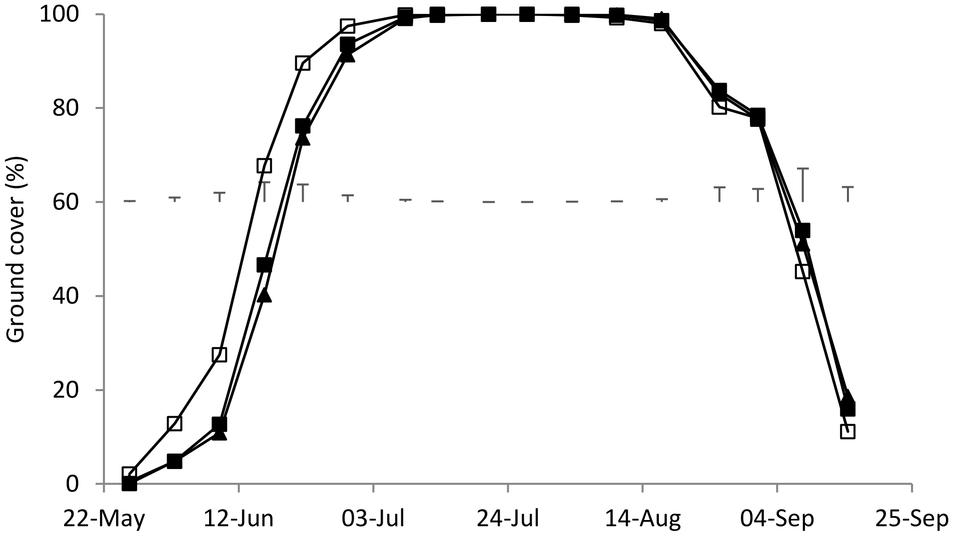


Table 28. Effect of cover crop treatment on integrated ground cover and radiation absorption in experiment 2020-74

Treatment	Integrated ground cover (% days)	Radiation absorption (TJ/ha)
Undefoliated	8152	13.38
Early Defoliation	8455	14.05
Late Defoliation	8061	13.21
S.E. (14 D.F.)	99.7	0.144

4.6.2.3. Yield at final harvest on 29 September

At final harvest, the mainstem population was 21 % greater for Early Defoliation (131700/ha) than for Undefoliated or Late Defoliation (mean 106200/ha) and the total number of tubers reflected this higher stem population since the number of tubers per stem was the same (4.7) across all treatments (Table 29). Small differences in emergence date can lead to differences in the radiation environment at tuber initiation and consequently differences in the number of tubers formed, but in this case the increase in number of tubers was manifested by an increased number of mainstems. The cause of this effect is conjecture but incorporating dead plant material (as opposed to living) in the seed bed of Early Defoliation might have changed the chemical profile of the soil or its porosity. Conversely, late defoliated and undefoliated cover crops may have resulted in accumulation of phytotoxic chemicals that did not have time to disperse before planting.

Total, marketable and DW tuber yields were all greater for the Early Defoliation than the Undefoliated or Late Defoliation treatments, whilst tuber [DM] was numerically slightly lower in Early Defoliation than the other two treatments (Table 29).

Table 29. Effects of cover crop treatment on components of yield and dry matter concentration in experiment 2020-74

Treatment	Total no. of tubers (000/ha)	Tuber FW yield (t/ha)	Yield > 40 mm (t/ha	Tuber DM concentration (%)	Tuber DW yield (t/ha)
Undefoliated	497	59.4	55.9	22.9	13.6
Early Defoliation	612	66.7	61.8	22.5	15.0
Late Defoliation	513	58.8	54.9	23.0	13.5
S.E. (14 D.F.)	19.8	1.26	1.23	0.25	0.34

4.6.2.4. Conclusions

The main hypothesis behind the experiment was that an actively growing cover crop would be able to dry the soil at cultivation depth, leading to an improved window for ploughing in spring compared with a bare stubble or cultivated soil surface. In fact, the opposite happened in that the cover crop (both undefoliated and desiccated) in two seasons acted as a surface mulch preventing the drying of the top 5 cm of soil. In 2020, the surface drying continued under a cover crop defoliated in March, but only because cultivation was delayed by 3 weeks in this season. Despite the canopy of the cover crop, soil drying under the cover crop at primary cultivation depth (*c*. 25-30 cm) did not begin until late March to early April in any of the three seasons. In 2020, the cover crop cultivations were delayed to magnify the effects of soil drying, but it was mid-April before substantial drying took place at primary cultivation depth.

There were very large differences in the DM yield (2.2-8.2 t/ha) and N uptake (54-133 kg N/ha by the cover crop over the 3 years despite the same cover crop, establishment technique and seed rate. The fate of the N taken up by the cover crop and incorporated into the soil is unknown. The cover crop experiment was supplied with the same N fertiliser (200 kg N/ha) as the other Maris Piper crops in the field and yields were similar suggesting a similar response to N irrespective of cover crop regime.

Despite the large yield increase (+7.3 t/ha) observed between Early Defoliation and Undefoliated cover crop treatments in 2020, over the three years of the cover crop experiment at NIAB, the overall effect was neutral (Undefoliated cover crop treatments averaged 61.6 t/ha, Early Defoliated treatments 61.1 1 t/ha), since there was an almost equivalent yield reduction (-5.5 t/ha) in 2018 caused by defoliating early compared with and undefoliated cover crop. In the two years when no cover crop was grown, Undefoliated cover crop treatments improved yield in one year and had no effect in the other when compared with no cover crop. In view of these contrasting effects on yield and the very late drying of soil at cultivation depth, growers may question whether the management effort close to the busy planting period is worth it, if it is possible to desiccate a cover crop 4-6 weeks ahead of planting with no detrimental effect? The direction of the response would depend very much on the rainfall and other weather conditions during the period between defoliation and planting. In one season, soil structure at cultivation was poor irrespective of cover crop management, but in 2018 structure was improved dramatically by having a cover crop versus nothing. In 2020, soil structure improved rapidly during April as soil dried and cover crop management had relatively little effect. Clearly, management of even quite a simple and cheap-to-establish cover crop needs an understanding of the likely benefits to be gained from leaving the cover crop to grow versus the trade-off in perhaps having to mow or flail the cover crop close to planting.

5. REPLICATED EXPERIMENT TESTING COVER CROPS AT BALRUDDERY

5.1. Replicated experiments done by the James Hutton Institute at Balruddery Farm, Dundee (2016-94, 2017-95 and 2018-96

As part of the project, the James Hutton Institute supplied data from a three-year experimental programme that tested the effects of over-winter cover crops on the yield of subsequent spring barley crops. This report summarises the materials and methods and results and conclusions. Full details may be found in Holland *et al*. (2021).

5.2. Materials and Methods

The three experiments, 2016-94, 2017-95 and 2018-96 were done at Balruddery Farm, Dundee. Details of the eight treatments tested in each experiment are shown in Table 30. Each treatment was replicated three times and allocated at random to blocks. Each plot was 6 m wide and 200 m long. The size of the plots facilitated use of commercial-scale farm equipment and thereby increased the applicability of the results to stake-holders. The cover crops were sown in early to mid-September in 2015, 2016 and 2017 use an Amazone combination seed drill together with fertilizer (30 kg N, 5.4 kg P, 19 kg K, and 4 kg S/ha). Cover crops were destroyed by ploughing at the end of March each year and the spring barley test crop was sown in early-April. In each year, the spring barley crop received a total of 110 kg N, 20 kg P, 70 kg K, and 15 kg S/ha. In 2017 and 2018, cover crop biomass was estimated by taking 1 m^2 quadrats from selected treatments. Yield of the spring barley crop was measured using a commercial scale combine. Grain nitrogen concentration was measured using near infra-red spectroscopy.

Soil water content under actively growing cover crops was measured using a Delta-T PR2 probe in all three experiments in selected treatments. Measurements were made at four depths (0-10, 10-20, 20-30 and 30-40 cm) at three locations in each replicate on several occasions but more frequently in March. The effect of cover crops on soil shear strength and water stable aggregates was measured using standard methodology (see Holland *et al.* 2021 for full details and references).

The effect of cover crop species on soil fauna (earthworms, slugs and nematodes) populations were also studied using standard methodologies. Earthworm populations were quantified by taking 30 × 30 × 30 cm cores in late March and quantifying the number of earthworms. Slug populations were also monitored in late March using refuge traps baited with chicken food mash. In late March 2017 and 2018, soil samples (20 randomly located, 2.3 cm diameter × 10 cm deep) were taken to assess populations of *Trichodorus*, *Pratylenchus* and spiral (*Helicotylenchus/Rotylenchus)* nematodes.

The impact of cover crops on financial performance of the spring barley crop was analysed by subtracting the cost of establishing and managing each cover crop from the value of the grain and straw. This analysis was based on 2019 prices. The impact of Ecological Focus Area (EFA) subsidies was also evaluated for all treatments except the control.

Table 30. Species composition of the cover crops in experiments 2016-94, 2017-95, 2018-96 at Balruddery Farm, Dundee

Treatment	Seed Rate (kg/ha)	Species and percent composition
Control	-	Mixture of weeds and volunteers from previous barley crop
Jupiter Turnip	12	Field mustard (100)
Structure Mix	25	Romessa oil radish (27); Winter oats (47), Rye (13), Phacelia (3) & Tillage radish (10)
Defender Oil	18	Oil Radish (100)
Radish Mix	20	Romessa oil radish (80) & Tillage Radish (20)
Vitality Mix	25	Romessa oil radish (24), Winter oats (38), Berseem clover (4), Strigosa oats (12), Phacelia (2) & Vetch (20)
Vetch & Rye Mix	40	Vetch (37) & Rye (63)
EFA Mix	20	Winter oats (80), White mustard (17.5) & Vetch (2.5)

5.3. Results and Discussion

On those treatments where it was measured, average cover crop dry matter yields varied from 0.14 t/ha (Structure mix) to 0.64 t/ha (Jupiter Turnip). For comparison, the average dry matter yield of the volunteers in the control plots averaged 0.14 t/ha. On average, spring barley yield were 7.7, 8.2 and 6.4 t/ha in 2016, 2017 and 2018, respectively. When average over the three seasons, use of cover crops resulted in a statistically significant (P=0.008) increase in grain yield when compared with control (Table 31). Increasing the proportion of brassicas in the cover crop mix was associated with a positive, linear effect on grain yield (P=0.001). On average, mixes with more than 20 % brassicas were associated with significant increases grain yield. Conversely, increasing the proportion of grass in the cover crop mix was associated with a linear decrease in the yield of the subsequent spring barley crop. Increasing the proportion of brassica in the cover crop mix was also associated with a linear increase in the nitrogen content of the grain. Use of a cover crop had no significant effect on 1000 grain weight which had a mean weight of 66.3 g. When averaged over the three season, financial output from the different treatments were estimated to vary from £1419/ha to £1515/ha in the Vetch and Rye mix and Defender Oil Radish, respectively (Table 31). Similarly, variable costs varied from £338/ha in the control to £429/ha with the Defender Oil Radish. When compared with the control, gross margins in the cover crop treatment were generally smaller, the exceptions being very small improvement in gross margin when Jupiter Turnip and Defender Oil Radish were used (Table 31). However, since these cover crops were eligible for payment under the Environmental Focus Area scheme, gross margins were better than the control, irrespective of cover crop mix when the EFA payment (*c*. £148/ha) was included in the calculations.

Table 31. Effect of cover crop treatments on average (2016-2018) yield of spring barley at Balruddery, Dundee

Treatment	Percent of brassicas and grass in mix	Spring barley yield and S.E (t/ha)	Value of grain output (£/ha)	Cover crop over control gross margin (£/ha)
Control	0, 100	7.24 ± 0.300	1422	-
Jupiter Turnip	100,0	7.47 ± 0.225	1468	3
Structure Mix	37, 60	7.49 ± 0.262	1471	-15
Defender Oil	100, 0	7.71 ± 0.290	1515	2
Radish Mix	100 ,0	7.61 ± 0.267	1494	-6
Vitality Mix	24, 50	7.41 ± 0.303	1456	-25
Vetch & Rye Mix	0, 63	7.23 ± 0.278	1419	-63
EFA Mix	18, 80	7.29 ± 0.295	1432	-43

When compared with the Control, use of a cover crop reduced soil water content, and whilst this was reduction was larger in the Defender Oil Radish Mix and in the Vitality Mix the effect was not significant. Surface shear vane strength was significantly reduced by using a cover crop. Use of cover crops had no significant effect on water stable aggregates < 2 mm. When compared with slug populations in the control plots, populations were reduced in the Jupiter Turnip and Structure Mix but increased in the Vitality Mix. In all cases, the slug population was below the AHDB threshold for remedial action. Whilst slug populations were relatively low, these results indicate the importance in the choice of cover crop treatment for the management of slugs which can be a serious crop pest particular in non-inversion tillage systems. The cover crops had no significant effects on earthworm or nematode populations. This series of experiments has demonstrated that cover crops can be established under challenging conditions in Northeast Scotland. At worst, the effect of cover crops on the yield of the subsequent spring barley crop was neutral but, in mixes containing brassicas there were statistically significant benefits. Due to the relatively limited number of seasons, it was not possible to fully evaluate the impact of the cover crops on soil processes and biota, but the results indicate these effects will be highly dependent on cover type and management

6. DATA ANALYSIS FROM GROWER PLATFORM SURVEY

At its inception it was realised that data gained from a five-year experimental programme was unlikely to fully answer questions about the agronomic and economic sustainability of current rotations and rotational practices used in the UK. To get a more complete picture, it was decided to construct a survey that would be sent to collaborating growers and agronomists. These survey data will:

- Help identify which kinds of rotational practices are associated with increased agronomic and economic sustainability
- Collect data on what cash crops are grown in the rotation, how the land is used between cash crops, what inputs (e.g., fertiliser, water, agrochemicals, organic amendments and diesel) are used and what is the output from each part of the rotation in terms of crop yield or livestock production
- Help inform the treatments tested in the on-farm experiments

6.1. Materials and methods

6.1.1. Data confidentiality

The Grower Platform surveys contain data that may be commercially sensitive and it is important that respondents to the survey were confident that the data they supplied were dealt with accordingly. At the inaugural Grower Platform meeting on 14 September 2016 the following data policy was agreed:

“We understand that the data you send us may be commercially sensitive. Data will be stored on secure servers within the project partnership. Contact details will be retained within the project partnership and not circulated to third parties. Similarly, crop location information will only be used for the purpose of obtaining soil mapping and meteorological data and only averaged or otherwise aggregated data will be published. We will not publish data that could be identifiable unless we have the express permission of all relevant parties.”

6.1.2. Questionnaires

The grower survey form was designed to be a simple as possible to complete but still collect robust information that would help fulfil the objectives of the Work Package. The design of the survey form was a collaborative effort between staff at NIAB and Katherine Preedy (JHI) and Yakubu Abdul-Salam (JHI).

Whilst it is intended that the survey should cover as many locations, rotation types and managements as possible, it must be noted that the survey is not intended to be a representative “snap-shot” of the practices underpinning UK crop production.

The grower survey forms were based around excel spreadsheets and data from each field are collected in one spreadsheet. A key feature of the survey is the division of time into discrete ‘intervals’. The interval is defined as a distinct period of land use and could therefore be whilst the land is producing a cash-crop, is being grazed by livestock, is producing a cover/catch-crop, is in stubble or is left bare after cultivation. For practical purposes, intervals of less than 7 days are ignored. Data for each interval are collected on a tab within the excel file. With this structure, once the surveys have been completed a detailed record of land-use is obtained. An example of the survey structure is shown in Figure 11.

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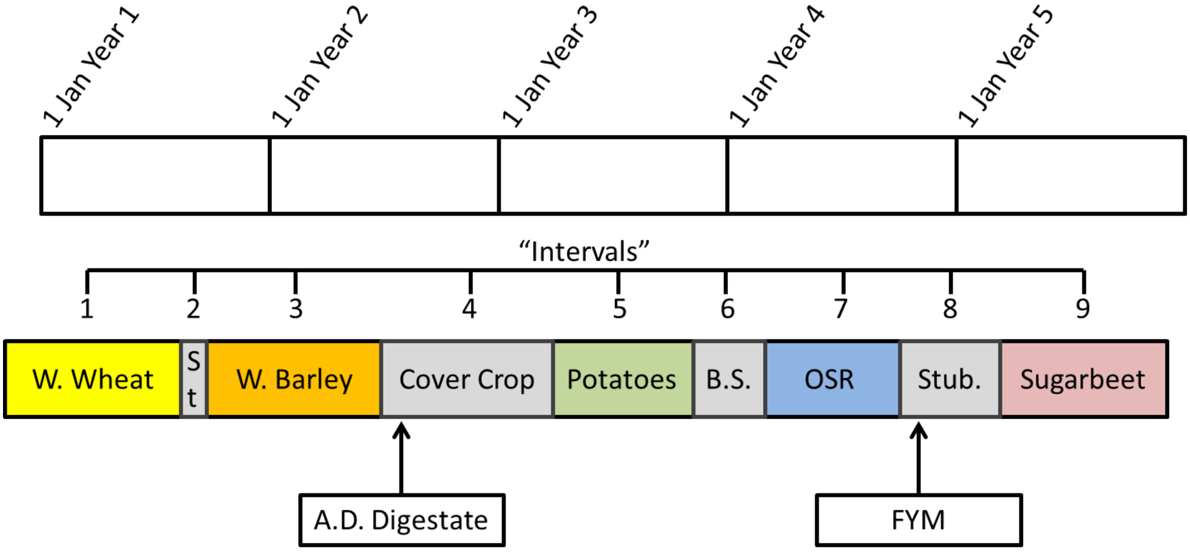
Figure 11. Structure of the Grower Platform survey showing the relationship between calendar year and land-use intervals.



The summary sheet at the start of each excel survey file contains a unique NIAB-generated field identification and a survey version number (Table 32). Grower contact information is also collected on this form, but this information will be removed before data are shared outside of the research partnership. Location data are also collected which will allow appropriate weather and soil data to be associated with this field. Information on surveyed area is compared with the declared cropped area to estimate the proportion of the field that is planted and to help sense-check estimates of yield. The survey form is designed to minimise ambiguous answers particularly to differentiate between no response to a question or "none" in answer to a question. Many of the answers to question are defaulted to "Not Specified" and growers are encouraged to change these to a response as they work through the form.

Table 32. Information needed on summary page

Information requested	Options and format
Field ID	Assigned by NIAB CUF
Landowner	User entered Free Text
Contact number	User entered telephone number
Contact e-mail	User entered e-mail address
Field Name	User entered Free Text
Surveyed area	User entered value – units preselected
Longitude	User entered as dd.dddd
Latitude	User entered as dd.dddd
OR OS Grid Reference	User entered as XX12345678
Year field was last in potatoes	User entered value
Survey version	v14022017

The first pieces of information required for describing a land-use is the current legal status (e.g., owned or rented) and whether it should be considered as part of a larger field (Table 33). The latter question is included, to allow for collection of data from fields that are amalgamations of smaller field that were once managed distinctly, or to allow fields to be split to reflect contrasting management applied to different areas of the field. An example of this may be if a cover crop were grown on part of a field or livestock were allowed to graze in one part of a field but not another. In this section, the respondent selects the type of land-use (crop, cover crop, stubbles, or grazing livestock *etc.*). In this section, growers are also asked to enter two sets of dates. The first pair is the interval start and finish dates, the second pair relate to the planting and harvest dates of crops. The survey contains a drop-down list of crop and cover crops (Table 34): should the crop not be included in the drop-down, there is an option for a user-defined entry. Respondents are also asked to enter their expected or planned yield when the crop was planted. This value can then be compared with the reported, achieved yield. Possible reasons for differences between planned and achieved yields and crop quality are explored in Table 35, with the permissible option listed in Table 36.

Table 33. Information about rotations and cropping

Information requested	Options
Version	14022017
Unique field ID	Created by NIAB CUF
Metric or imperial units	Not Specified
	Metric
	Imperial
Land Legal Status	Not Specified
	Owned
	Contract farmed
	Full tenancy
	Short term tenancy (FBT or equivalent)
	Seasonally rented in land
Part of larger field	Not Specified
	No
	Yes
Cropping in this interval (including cover crops)	See separate listing in table 34
Cropping (if 'Other' selected)	User entered Free Text
Expected gross yield for this crop	User entered value – units preselected
Cropped/livestocked area	User entered value – units preselected
Interval start date	User entered value (dd-mmm-yyyy)
Interval finish date	User entered value (dd-mmm-yyyy)
Crop planting date (start)	User entered value (dd-mmm-yyyy)
Crop harvest date (start)	User entered value (dd-mmm-yyyy)
Livestock type	Not Specified
	None
	Cattle (Dairy)
	Cattle (Beef)
	Goats
	Horses
	Pigs
	Poultry
	Sheep
Approx. stocking rate	User entered value – units preselected
Livestock put into field	User entered value (dd-mmm-yyyy)
Livestock removed from field	User entered value (dd-mmm-yyyy)

Table 34. Options for cropping in an interval (including cover crops)

Cropping	Cropping
Not Specified	Forage Maize
Barley (Feed - Spring)	Oat, Rye & Triticale (Spring)
Barley (Feed - Winter)	Oat, Rye & Triticale (Winter)
Barley (Milling - Spring)	Oil Seed Rape (Spring)
Barley (Milling - Winter)	Oil Seed Rape (Winter)
Bare soil following previous crop	Onions
Brussel Sprouts	Other - (Please Specify)
Cabbage	Parsnips
Carrots	Ploughed
Cauliflower	Potatoes (Maincrop)
Cover crops (single-species)	Potatoes (Salad)
Cover crops (multi-species)	Potatoes (Seed)
Field Beans (Spring)	Stubble following cereal
Field Beans (Winter)	Stubble Turnips
Forage Rape	Sugar beet
Forage Swedes & Turnips	Swedes
Grassland (less than 2 years old)	Vining Peas
Grassland (2- 5 years old)	Wheat (Feed - Spring)
Grassland (more than 5 years old)	Wheat (Feed - Winter)
Leeks	Wheat (Milling - Spring)
Linseed	Wheat (Milling - Winter)

Table 35. Grower information about factors that have detracted from yield and quality potential

Information requested	Yield	Quality
1. Weed population		
2. Soil pest populations (e.g., slugs, potato cyst nematodes etc.)		
3. Top-soil structure (e.g., cloddiness, capping etc.)		
4. Sub-soil structure (compaction)		
5. Organic matter content		
6. Soil nutritional (e.g. P, K, Mg & S) status		
7. Soil moisture content (e.g., droughty or water-logged poor drainage)		
8. Effect of foliar diseases		
9. Effects of soil-borne diseases		
10. Position in rotation		
11. Weather conditions prior to and at planting		
12. Weather condition during the growing season		
13. Weather conditions during harvest		

Table 36. Options for Table 35

Not Specified

1. Had no effect on current crop

2 - Had small negative effect on current crop

3 - Had large negative effect on current crop

4 - Had v. large negative effect on current crop

Table 37 allows the agronomist or grower to add information about any soil tests done in the current interval. Apart from basic soil analysis (pH, extractable P and exchangeable K and Mg), there is also an option to include the organic matter content of the soil. Other soil properties (e.g., soil texture) can be obtained from soil maps or databases using the location data given in Table 32. Some information is also collected on the strategies adopted to minimise soil damage as shown in Table 38.

Table 37. Request for information on soil analysis taken during the current interval

Date of sample	User entered value (dd-mmm-yyyy)
Top soil pH	User entered value
Soil extractable phosphate (P)	User entered value – units selected from list
Soil exchangeable potassium (K)	User entered value – units selected from list
Soil exchangeable magnesium (Mg)	User entered value – units selected from list
Soil organic matter (OM)	User entered value – units selected from list

Table 38. Request for information about strategies to minimise soil damage

Information requested	Options
What type of system is used to minimise soil damage?	Not Specified None Controlled wheelings Low ground-pressure equipment

A significant proportion of the cost of crop production is associated with the cultivation used to establish and then harvest the crop. Table 39 lists the possible cultivations and operations whilst Table 40 gives options for the size of tractor or harvester used for each operation. Should the operation not be listed, the respondent has an option for adding that operation as free-text. The respondent also says how many times each operation was done so that, collectively, the data can be analysed to estimate how much energy has been consumed in the interval.

Table 39. Information requested about types of cultivations used in the current interval. Growers are also asked about the number of each operation and the size (power) of the machinery used

Cultivation/operation	Cultivation/operation
Bed-form	Single pass drilling ('strip tillage')
Bed-till	Plant/Drill
Broadcast/autocast	Plough
Apply amendments	Plough & Press
Destone	Rotavate
Direct drill into stubble	Rake/trash rake
Non inversion tillage (shallow < 10 cm)	Sub-cast
Non inversion tillage (deep > 10 cm)	Sub-soil
Drill/Plant	Apply fertiliser
Harvest	Other (user entered text)

Table 40. Options for size of machinery used for operations listed in Table 39

Not Specified
< 100 hp (< 75 kW)
100-200 hp (75-150 kW)
200-400 hp (150-300 kW)
400-600 hp (300-450 kW)
> 600 hp (> 450 kW)

Table 41 illustrates the information collected relating to crop residue management. The quantities of residue removed (or retained) is estimated from the crop type (Table 34) and the yield of the crop (Table 47).

Table 41. Information requested about crop residue management in the current interval

Information requested	Options
Crop Residue management	Not specified
	Not applicable
	Retained in field
	Exported from field

Inputs of agrochemicals, fertiliser and irrigation water are collected in Table 42, Table 43 and Table 44, respectively. The survey collects information on the types of products (e.g., nematicide, desiccant) but not on the specific products. However, when combined with industry average product costs, these data will be useful in estimating the total cost of agrochemical usage in the current land-use interval. Similarly, Table 43 collects data on inputs of manufactured fertilisers and liming products in the current interval from which inferences can be made as to cost. In Table 44, the respondent details how much irrigation water was applied to the crop, the method of application (e.g., rain-gun or fixed-sprinklers) and the method of scheduling the irrigation application. Again, this information can be analysed to estimate the costs of irrigation water applications.

Table 42. Request for information relating to use of agrochemical in the current interval

Information requested	Options
Number of nematicide applications	Not specified
Number of molluscicide application	0
Number of insecticide applications	1 to 20
Number of plant-growth regulator applications	
Number of herbicide & desiccant applications	
Number of fungicide applications	

Table 43. Request for information about applications of fertiliser and liming products in current interval

Information requested	Options
Total N application to crop	User entered value – units selected from list
Approximate percent of N applied as urea	Not specified
	Approx. 0-25 %
	Approx. 25-50 %
	Approx. 50-75 %
	Approx. 75-100 %
Total P application to crop	User entered value – units selected from list
Total K application to crop	User entered value – units selected from list
Liming material	User entered value – units selected from list

Table 44. Request for information about applications of irrigation in current interval

Information requested	Options
Total amount of water applied to crop	User entered value – units selected from list
Method of application	Not Specified
	Boom & reel
	Fixed sprinkler
	Gun & reel
	Linear move
	None
	Drip Tape
Method of scheduling irrigation	Not Specified
	Balance sheet (e.g., CUF or Irriguide)
	Field assessment
	Neutron probe
	None
	Other
	Soil moisture sensors

Table 45 (with the options contained in Table 46) obtains information on the types of organic amendment applied within the current interval. Apart from the type of amendment, growers and agronomist are also asked to supply information on the estimated cost of the amendment (if imported into the field), date and rate of application and an estimate of the distance the product had to be transported from its source to its point of use. Information of the dry matter concentration of the amendment can be used as a proxy for nitrogen (and carbon) content and can be used to refine estimates of the value of the amendment.

Table 45. Request for information amendments applied to the field in the current interval

Information requested	Options
Type of amendment	See separate listing in Table 46
Estimate of cost/value of amendment	User entered value – units selected from list
Date of amendment	User entered value (dd-mmm-yyyy)
Rate of application	User entered value – units selected from list
Approx. transport distance to field	User entered value – units selected from list
If known, the dry matter content of the amendment	User entered value – units selected from list

Table 46. Options for types of amendments specified in Table 45

Not Specified	FYM Cattle
None	FYM Pig
Biosolids Composted	FYM Sheep
Biosolids Digested Cake	Paper Crumble
Biosolids Thermally Dried	Poultry Manure
Compost Greenwaste	Slurry Cattle
Compost Municipal	Slurry Pig
Digestate Separated Fibre	Straw from previous crop
Digestate Separated Liquor	Straw imported from another field
Digestate Whole	

In the final part of the survey, the grower is asked to estimate the yield of the crop and, so that the answer, can be given due weighting, the method used to assess the yield. When combined with standard, industry figure, the information on yield can be used to estimate gross economic value of the crop in the current land use interval.

Table 47. Request for information relating to yield and its estimation in the current interval

Information requested	Options
Estimate of gross production OR	User entered value – units selected from list
Estimate of gross yield	User entered value – units selected from list
Method used to estimate production	Not Specified
	None
	Box-counts
	Trailer & weight bridge
	Yield monitoring harvester
	Yield samples

Questionnaires were e-mailed to Platform members and in addition, questionnaires were promoted at Potatoes in Practice events hosted by The James Hutton Institute in 2016 and 2017. When responses were low NIAB conducted an extensive programme of on-farm engagement to collect data which was extensively quality checked and unusual entries checked with farmers. It was then collated to form a resource for the following analysis, for the economic modelling objective, the Soil Health Scorecard project and as a resource for future analysis. To allow analysis of low frequency crops, the were mapped onto broader Crop categories listed in Table 48.

Table 48. Crops and the crop category they have been mapped on to together with the frequency with which they occur

Crop	Crop Category	Frequency
Bare soil following previous crop	Bare	78
Over wintered stubble with oil radish	Bare	1
Ploughed	Bare	4
Stubble following cereal	Bare	135
Barley (Feed - Spring)	Barley	8
Barley (Feed - Winter)	Barley	11
Barley (Milling - Spring)	Barley	16
Barley (Millling - Winter)	Barley	7
Spring Barley - Seed	Barley	4
Cover crops (multi-species)	Cover	8
Cover crops (single-species)	Cover	13
Grassland (2- 5 years old)	Grass	2
Grassland (less than 2 years old)	Grass	5
Grassland (more than 5 years old)	Grass	1
combining peas	Legumes	1
Field Beans (Spring)	Legumes	5
Peas - Large Blue	Legumes	1
Vining Peas	Legumes	11
Forage Maize	Maize	15
Oat, Rye & Triticale (Winter)	Oats	1
Oat, Rye & Triticale (Spring)	Oats	5
Oats	Oats	2
Kale/Rape Hybrid	OSR	1
Linseed	OSR	2
Oil Seed Rape (Winter)	OSR	41
Potatoes (Maincrop)	Potatoes	49
Potatoes (Salad)	Potatoes	4
Potatoes (Seed)	Potatoes	3
Carrots	Roots	7
Fodder Beet	Roots	1
Forage Swedes & Turnips	Roots	1
Onions	Roots	4
Parsnips	Roots	2
Stubble Turnips	Roots	6

Table 49. Crops and the crop category they have been mapped on to together with the frequency with which they occur (continued)

Crop	Crop Category	Frequency
Sugarbeet	Roots	25
Asparagus	Veg	1
Calabrese	Veg	3
Cauliflower	Veg	6
Leeks	Veg	2
Wheat (Feed - Spring)	Wheat	2
Wheat (Feed - Winter)	Wheat	81
Wheat (Milling - Spring)	Wheat	1
Wheat (Milling - Winter)	Wheat	48
Winter wheat - for seed	Wheat	6

There is incomplete information as to field ownership, and within that, it is not clear which fields are part of the same rotation. The assumption has therefore been made that each field is independent. Summaries of management practices and yield for different crops have been computed and differences between treatments have been assessed using t-tests. Key questions which the data set contained sufficient information to address were identified as follows:

- Do organic amendments or cover crops make a difference to yield, nitrogen or agro-chemical applications in Potatoes and Wheat?
- Do potatoes and or root veg in the rotation make a difference to yield, agro-chemical applications and nitrogen required in wheat?
- Is there a relationship between nitrogen or agro-chemical inputs and yield?

In June 2021 a second data set was received which increased the numbers of observations in each category as can be seen from Table 50. The field operations were modified to reflect the priorities of the soil health scorecard system focussed on cultivation operations and the original field operations were mapped onto them as in Table 51. There was an increase in instances of Barley, Cover Crops, Grass, Legumes, Oilseed Rape, Root Vegetables and Wheat and the new data set contained site specific information such as assessed soil texture and region.

Table 50. Number of intervals containing each crop category in the initial data set and in the combined data sets

Crop Category	First frequency	Second frequency	Total frequency	Frequency with yield data
Bare	212	35	247	232
Barley	46	33	79	73
Cereals	0	3	3	3
Cover	20	31	51	50
Grass	9	16	25	25
Legumes	17	21	38	34
Maize	15	4	19	18
Oats	8	4	12	12
OSR	44	49	93	84
Pigs	0	1	1	1
Potatoes	56	1	57	55
Roots	46	14	60	54
Veg	5	0	5	5

It had been hoped that the second data set would provide an opportunity to test the hypotheses found to be significant from the first data set. However, there was insufficient data on the crops found to have significantly different yields under varying rotational practices. The data comes from farms that have an involvement with NIAB through prior collaborations on targeted projects (including the AHDB Soil Biology Soil Health Partnership project) and includes experimental sites with a focus on grass and cereals so whilst suitable for characterising rotation management and testing the effects of specific practices (such as livestock) they are not suitable for benchmarking. Therefore, visual checks were made to ensure that the distribution of management practices (such as area cropped, agro-chemical applications and cultivations) were not markedly different to those from the original data set. The data sets were then combined to provide greater power to investigate the effect of rotational practices on yield.

Table 51. Original Categories and the categories from the second data set related to the soil health scorecard to which they have been mapped. There was no equivalent of Roll in the initial data set and Harvest/chemical applications have not been recorded as cultivations in the second data set

Original Categories	New Categories
Bed-Form	Bed form / ridging
Bed-Till	Bed form / ridging
Destone	Destone
Broadcast/autocast	Direct drill / zero tillage
Direct drill into stubble	Direct drill / zero tillage
Drill/Plant	Direct drill / zero tillage
Plant/Drill	Direct drill / zero tillage
Apply amendments	-
Harvest	-
Sub-cast	-
Apply fertiliser	-
Non inversion tillage (deep > 10 cm)	Non inversion tillage (deep > 10 cm)
Non inversion tillage (shallow < 10 cm)	Non inversion tillage (shallow < 10 cm)
Plough	Plough
Plough & Press	Plough and press
	Roll
Rotavate	Rotavate
Rake/trash rake	Straw rake or equivalent
Single pass drilling ('strip tillage')	Strip tillage
Subsoil	Subsoil

- Do organic amendments or cover crops make a difference to yield, nitrogen or agro-chemical applications in Potatoes, wheat, barley, OSR and root vegetables?
- For Wheat, barley and OSR do potatoes or root vegetables in the rotation make a difference to yield, agro-chemical applications and nitrogen required?
- For potatoes, root vegetables, wheat and barley, does OSR in the rotation make a difference to yield, agro-chemical applications and nitrogen required?
- Does livestock in the rotation make a difference to yield agro-chemical applications and nitrogen required?
- Is there a relationship between nitrogen or agro-chemical inputs and yield?

Several of the records from the second data set contained no yield data, but good information on rotational and management practices so they were incorporated into an analysis to characterise rotational practices to support analysis in the AHDB Soil Biology Soil Health project. The results are incorporated into the soil health project report.

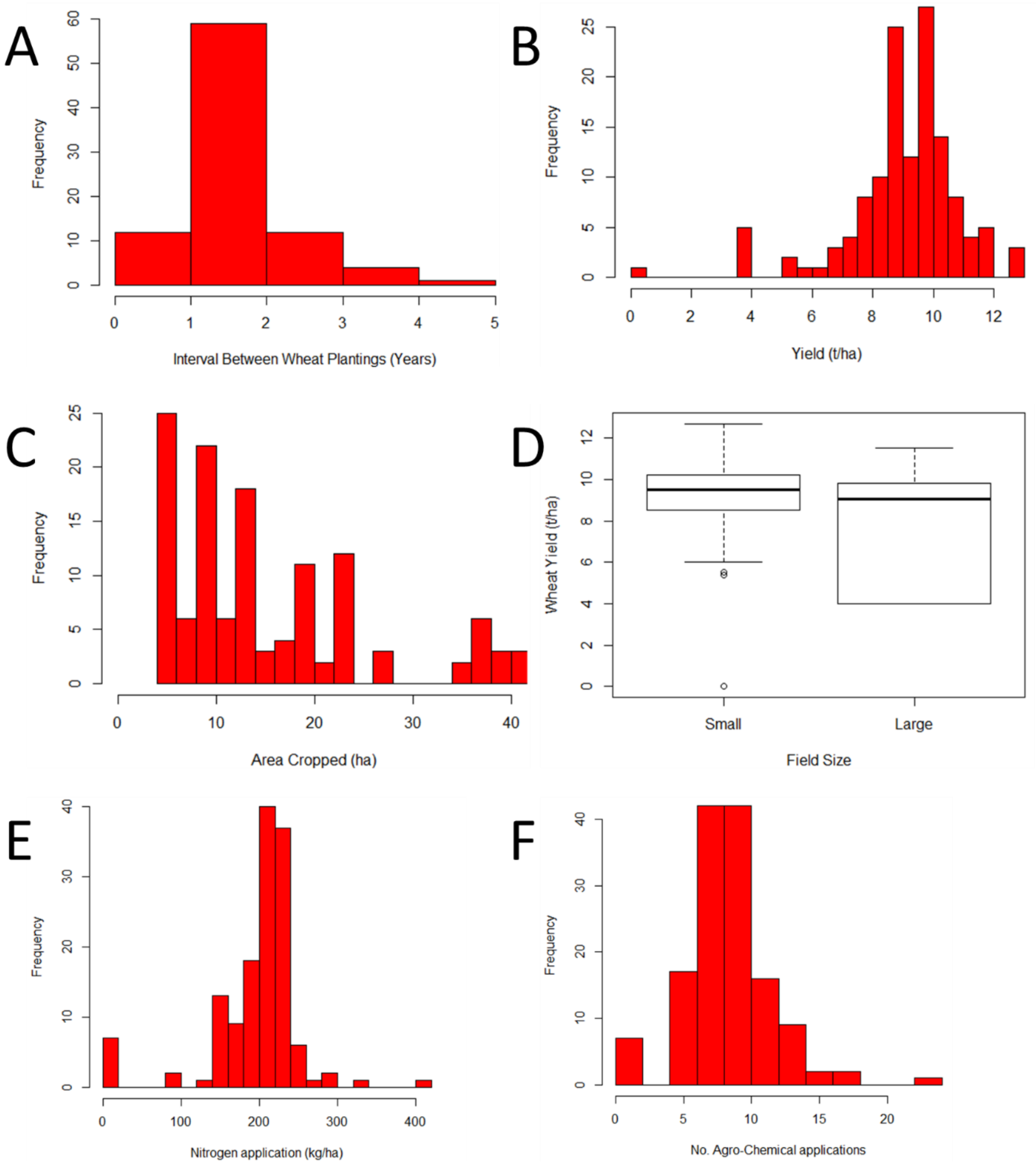
6.2. Results

6.2.1. Summary data of the main crop categories

6.2.1.1. Wheat

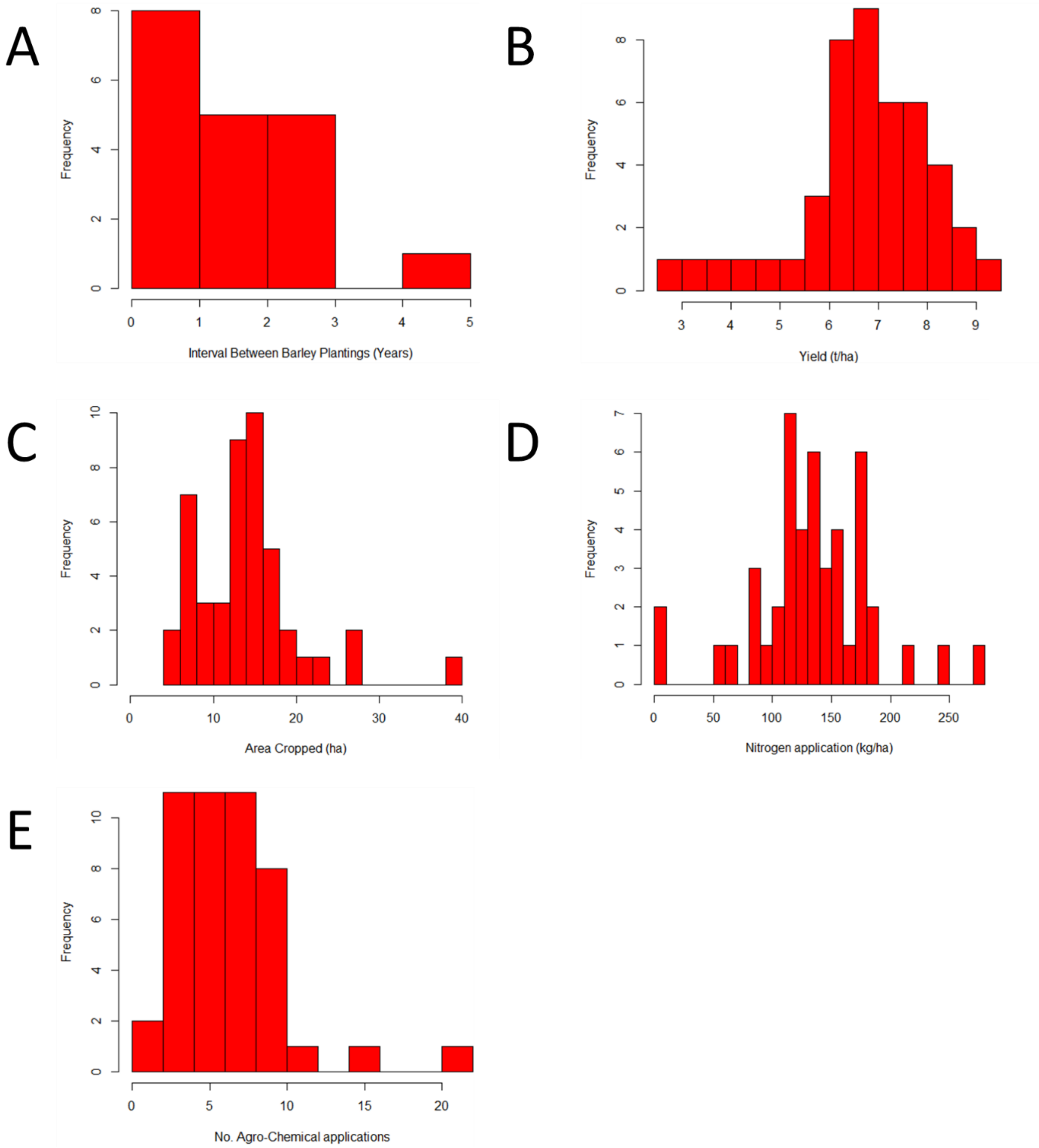
138 intervals from 26 out of the 30 known owners and 50 of the 56 fields. 5 fields have missing yields and one field had a total crop failure. Wheat was planted anything between in concurrent years and every 5 years with the most common pattern being planting every other year. Figure 12(A) and Figure 12(B) shows the distribution of yields. Except for the crop failure, the mean yield was 9.2 t/ha (S.E. 0.15) and the area cropped was vary variable with most field being 4-24 hectares, but a cluster of large fields of 36-40 ha (Figure 12(C). The yield per hectare is marginally lower on larger fields (>30 ha) (Figure 12(D). If the crop failure is excluded from the analysis smaller field have a mean yield of 9.39 t/ha (S.E. 0.15) and large fields 7.85 t/ha (S.E. 0.69) (t=2.18 on 16.1 D.F., p=0.045), despite there being no significant difference between the amount of nitrogen (t=1.4293 on 17.7 D.F., p=0.17) or agrochemicals applied (t= -0.94 on 16.5 D.F., ==0,36). Overall mean nitrogen application was 201 kg/ha (S.E. 5.1) with one field receiving over 400 kg/ha (see Figure 12(E) and the mean number of agrochemical applications was 8.73 (S.E. 2.88) (see Figure 12(F) for overall distributions).

Figure 12. Summary data of the main crop categories – wheat. (A) Interval between Wheat plantings (Years). The most common planting pattern is every other year. (B) Wheat Yields across all years and fields in the rotation. 5 fields had missing yields and one field had a total crop failure. (C) Wheat area cropped.(D) Wheat Yield by field size (Large fields are those >30 ha) (116 small fields and 16 large fields). (E) Nitrogen applications to Wheat crops (F) Number of Agrochemical applications to each wheat crop.



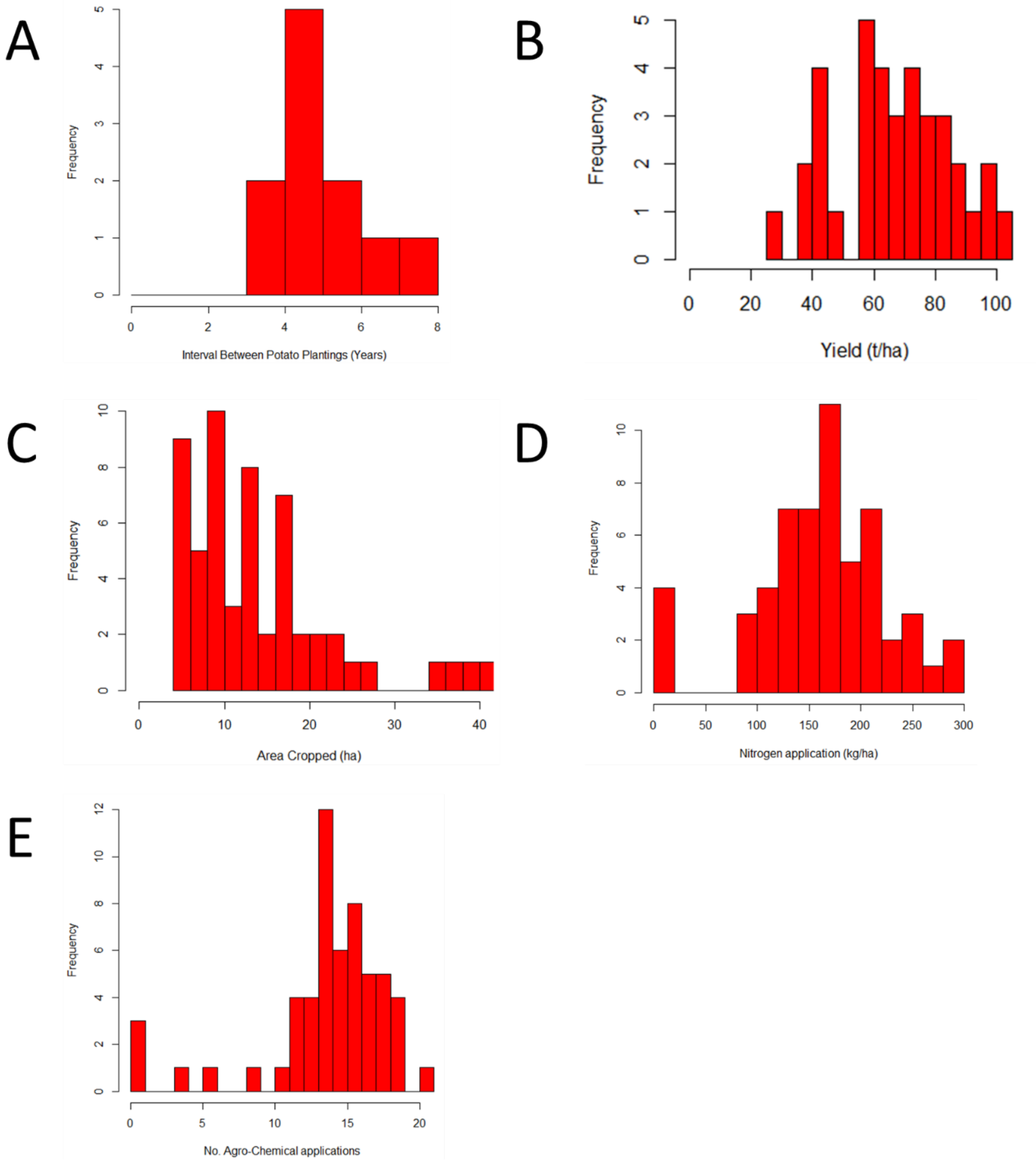
There are 46 instances of barley in 27 fields and 21 known owners. 1 field has missing yield data. Intervals between barley planting varied between every year and intervals of 5 years (Figure 13(A)). Figure 13(B) shows the distribution of yields. The mean yield was 6.81 t/ha (S.E. 0.21) with the area cropped being very variable with most fields being 4-24 hectares (Figure 13(C)). Mean nitrogen applied was 136 kg/ha (S.E 7.6) and the mean number of agrochemical applications was 6.72 (S.E. 0.54) (See Figure 13(D) and (E) for the distribution of nitrogen and agrochemical applications respectively).

Figure 13. Summary data of the main crop categories – wheat. (A) Interval in years between successive barley plantings where it has occurred more than once in a field. (B) Barley yields across all years (t/ha). (C) Area cropped for barley plantings across all years. (D) Nitrogen application to each barley crop (kg/ha). (E) Number of Agro-Chemical applications to each Barley Crop.



There are 56 instances of potatoes in 45 fields and 25 known owners. Two fields have missing yield data. Intervals between potato planting varied between three and eight years (Figure 14(A) and (B) shows the distribution of yields. The mean yield was 47.36 t/ha (S.E. 1.56) and the area cropped was very variable with most fields being 4-27 hectares (52 fields), but a cluster of large fields of between 36-42 ha (4 fields) (Figure 14(C)). Mean nitrogen applied was 165.4 kg/ha (S.E 8.92) and the mean number of agrochemical applications was 14.1 (S.E. 0.60) (See Figure 12(D) and (E) for the distribution of nitrogen and agrochemical applications, respectively).

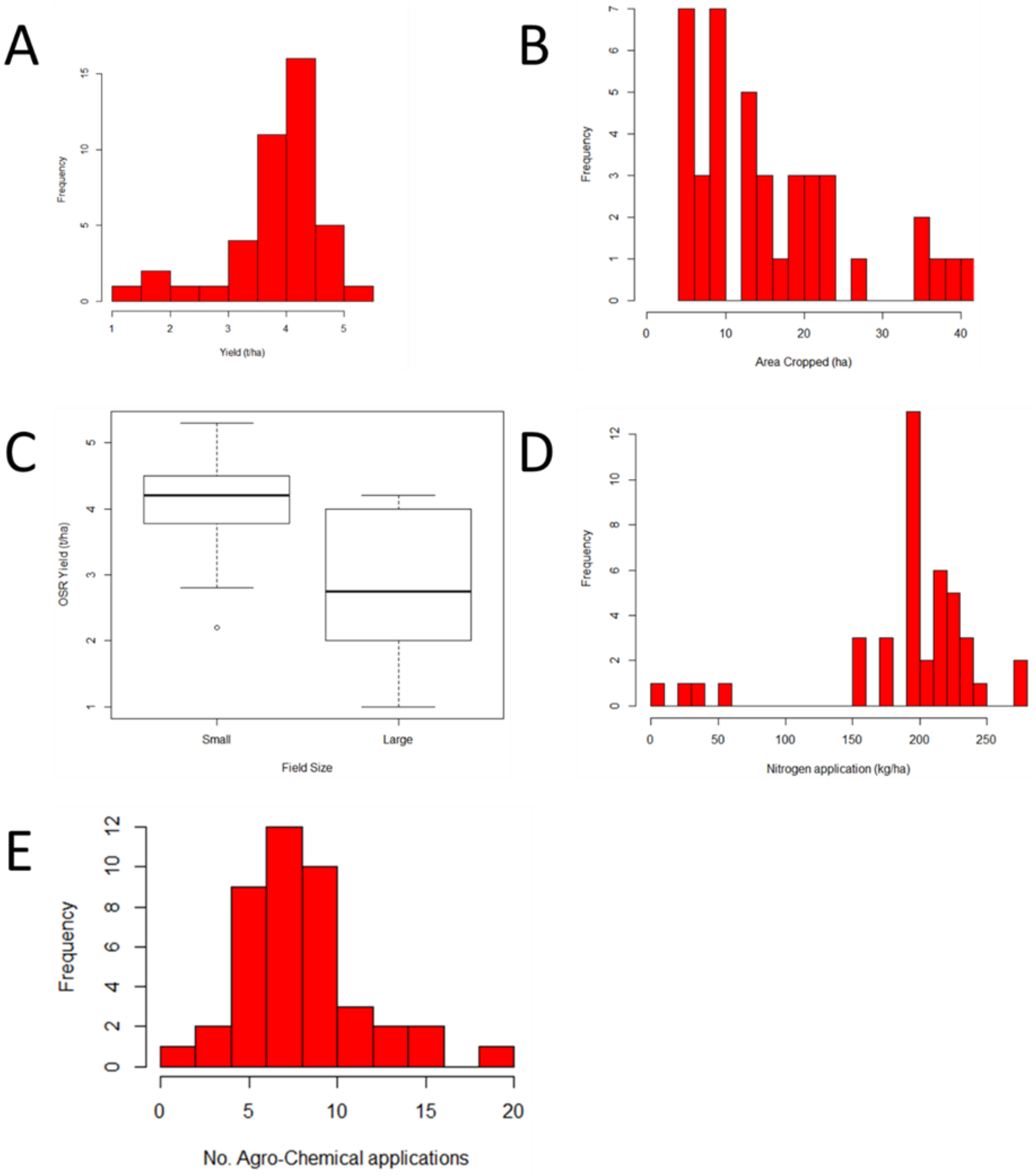
Figure 14. Summary data of the main crop categories – wheat. (A) Interval in years between successive potato plantings where it has occurred more than once in a field. (B) Potato yields across all years (t/ha). (C) Area cropped for potato plantings across all years. (D) Nitrogen Applications to potato crops (t/ha). (E) Number of Agro-chemical applications to potato crops.



6.2.1.2. OSR

The Kale/Rape Hybrid was excluded from the analysis as the yield of 20 t/ha, which is more than four times most OSR crops. 44 intervals were associated with OSR, from 19 out of the 30 known owners and 34 of the 56 fields. 2 fields have missing yields. OSR (or similar) was either planted once in the current data set or every other year in the eight fields where it occurred twice. Figure 15(A) shows the distribution of yields. The mean yield was 3.9 t/ha (S.E. 0.13) and the area cropped was very variable with most fields being 4-24 hectares (36 fields), but a cluster of large fields of 36-40 ha (six fields) (Figure 15 (B)). The yield per hectare is marginally lower on larger fields (>30 ha) (Figure 15(C)). Small fields have higher yields than large fields (t=2.51 on 5.37 D.F., p=0.05) despite there being no significant difference between the amount of nitrogen (t=1.063 on 6.66 D.F., p=0.33) or agrochemicals applied (t= 0.13 on 5.84 D.F., =0.89). However, there were only six larger fields. Mean nitrogen application was 201 (kg/ha) (S.E. 5.1) (Figure 15(D)) shows the full distribution). The mean number of agrochemical applications was 8.73 (S.E. 2.88) (See Figure 15(E) for the full distribution).

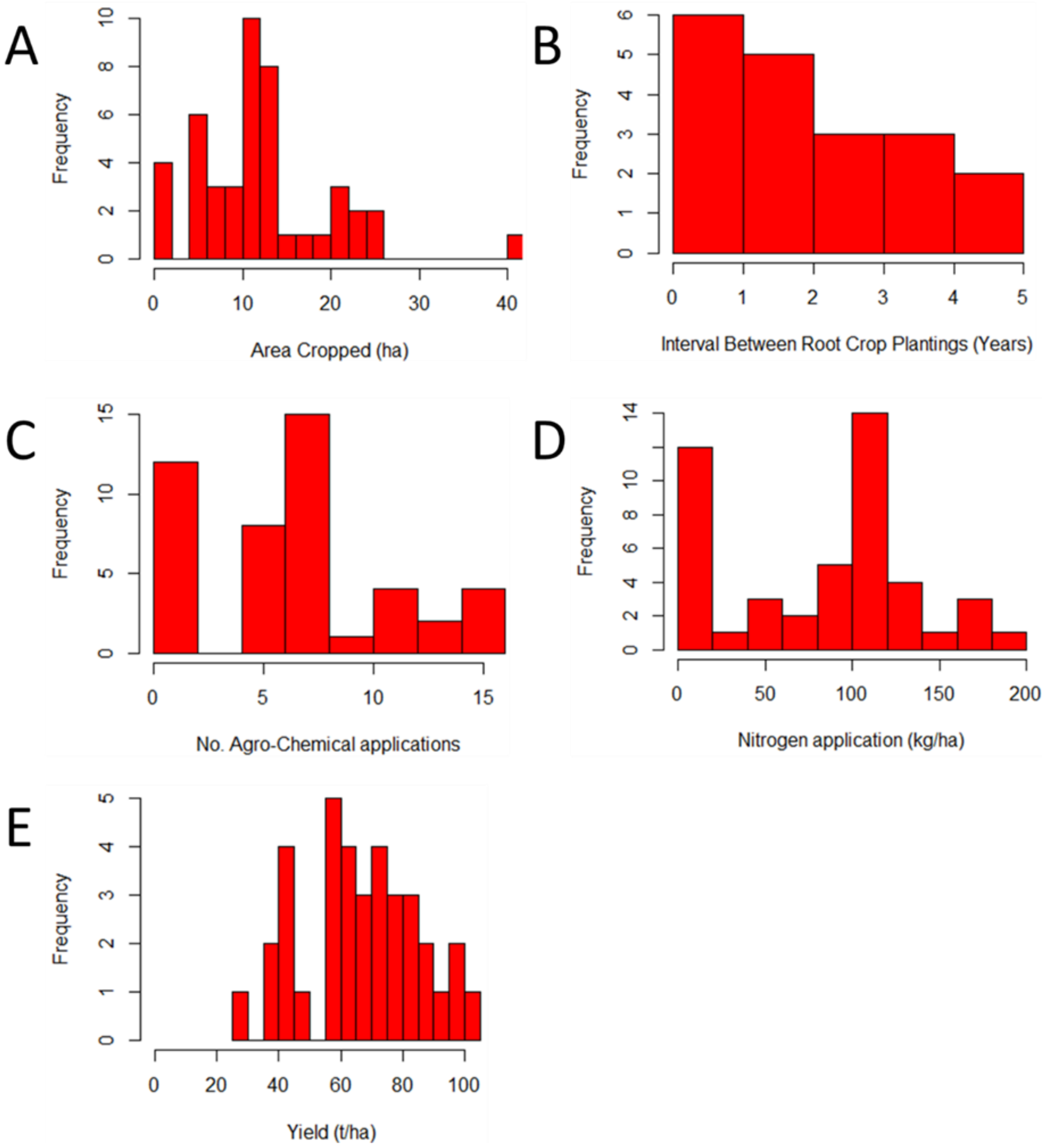
Figure 15. Summary data of the main crop categories – OSR. (A) OSR yields (t/ha) across all years of the rotation. 2 fields had missing yields. (B) OSR area cropped. (C) OSR yield by field size (36 small fields and 6 big). Large fields are those >30 ha. (D) Nitrogen Applications to OSR crops (t/ha). (E) Number of Agro-chemical applications to OSR crops.



6.2.1.3. Root Crops

There were 46 intervals of root crops and the area cropped tended to be lower than when cereals were planted in the same field. 17 out of the 30 owners planted them in 27 out of the 56 fields though some only planted Stubble turnips. There was one instance with missing yield and nine instances of zero yield – six of stubble turnips which are unlikely to have been harvested, one of forage swedes, also unlikely to have been harvested and one of carrots. These were all excluded from the yield analysis, but nitrogen and agrochemical treatments were applied so they have been retained in the other summary statistics. The area cropped tended to be between 4 and 26 hectares with only one field of over 40 hectares (Figure 16(A). The fields with zero area cropped were all Stubble turnips and therefore likely to be reported as such because of zero harvest. There were 14 fields with more than one instance of root crops and the interval between crops varied between planting in the same year and five years between plantings (Figure 16(B)). The mean number of agro-chemical applications was 6.6 (S.E. 0.71) and 12 instances had no agro-chemical applications (Figure 16(C)). The mean nitrogen applied was 84.8 kg/ha (S.E. 8.85) and 12 instances had no nitrogen applied (Figure 16(D)). Mean Yield was 67.57 t/ha (S.E. 3.12) (Figure 16(E)).

Figure 16. Summary data of the main crop categories – Root Crops. (A) Area Cropped for Root vegetables. Instance of 0 area cropped are all Stubble Turnips. (B) Interval between root crop plantings where there is more than one instance in the field. (C) Number of Agro-chemical applications to Root Crops. (D) Amount of nitrogen applied to root crops (kg/ha). (E) Yield from root crops (t/ha).



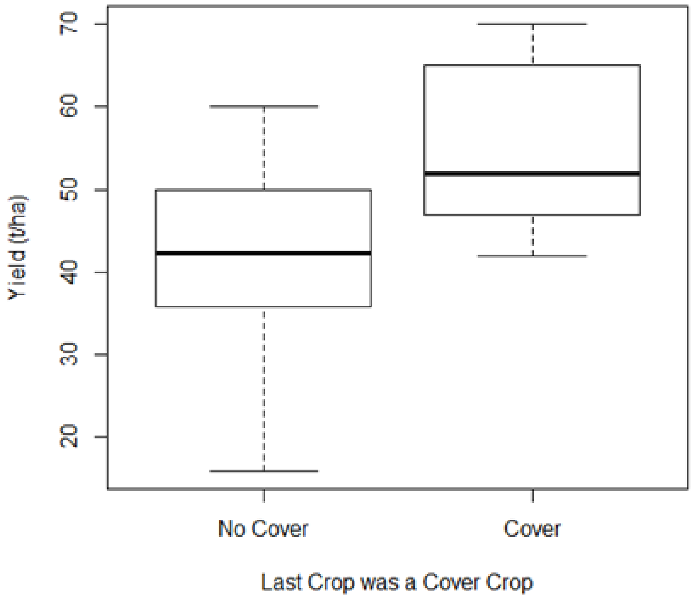
6.2.2. Rotational Effects

6.2.2.1. Cover Crops

There were 21 intervals as cover crops in 16 fields. In 14 instances, potatoes were the next crop planted after the cover intervals of which 10 have associated yield data and there are 31 instances where they were planted with no preceding cover crop, but one of these has no yield data and is therefore excluded from the analysis. There is insufficient data to consider the second crop planted after cover crops.

There was no significant difference in the amount of nitrogen applied or the number of agro-chemical applications, but yield from potatoes planted after a cover crop was significantly higher than those where there was no cover crop (t=3.88, df=25.95, p=0.00064) with those after a cover crop having a mean of 54.8 t/ha (S.E. 2.64) as opposed to 42.3 t/ha (S.E. 1.84) (see Figure 17).

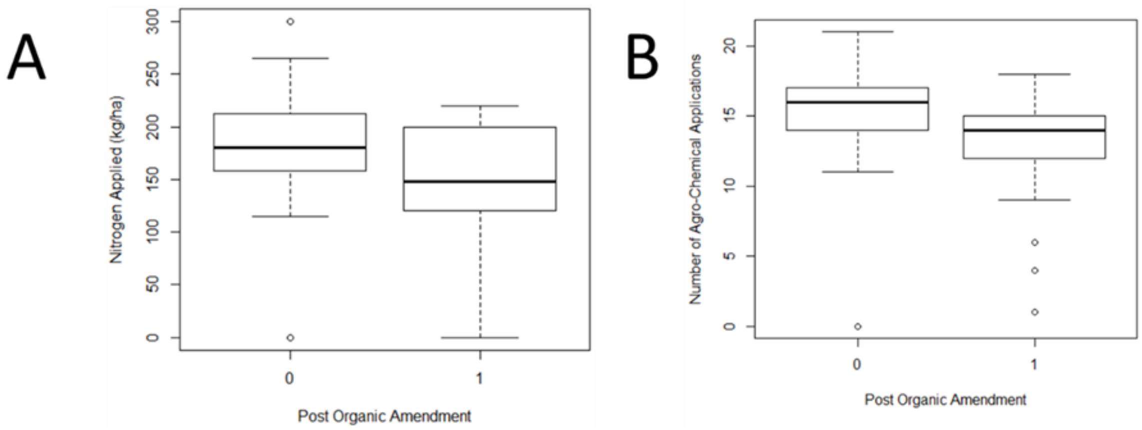
Figure 17. Rotational Effects – Cover crops – Potato yields split by whether the preceding crop was a cover crop.



6.2.2.2. Organic Amendments

In the survey, 37 fields had organic amendments applied. There were 22 intervals where the next planted crop was wheat and 19 where the next planted crop was potatoes. There were 14 instances where wheat was the second crop planted after application of organic amendments. The yield, nitrogen applied and number of agro-chemical applications from the first and second crops planted after the organic amendment was compared to crops where there was no preceding organic amendment, but there was no significant difference for any of these treatments for wheat. For potatoes, there were 18 intervals after an organic amendment where the yield was known and 27 intervals where no organic amendment was applied. There was no significant difference in yield, but marginally lower nitrogen (t=1.89 on 38.8 D.F., p=0.066) and marginally fewer agro-chemical applications (t=2.14 on 31.9 D.F., p=0.04) (Figure 18(A) and (B), respectively). There was insufficient data to compare other crops.

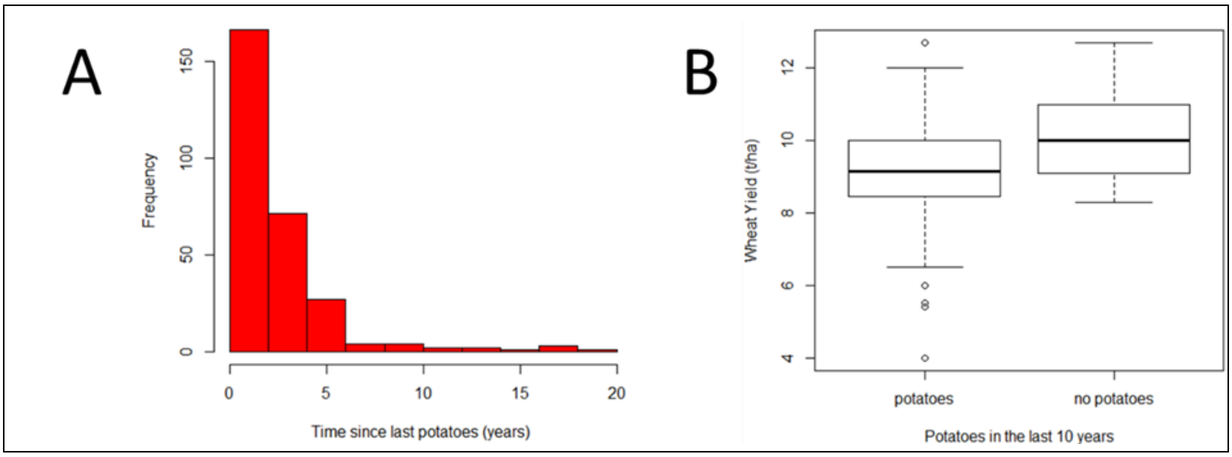
Figure 18. Rotational Effects – Organic amendments. (A) Nitrogen applied to potato crops 0 is crops planted after no amendment has been applied, and 1 is crops planted after an organic amendment. There was no significant difference in yield. (B) Number of Agro-chemical applications to potato crops 0 is crops planted after no amendment has been applied, and 1 is crops planted after an organic amendment. There was no significant difference in yield.



6.2.2.3. *Potatoes*

The number of intervals per field varies and many fields do not have data for a complete rotation and not all intervals had information on time since the last potato crop. In these instances, where possible the time was calculated from the crop data. If there was no information on potatoes, and no record of potatoes in the crop data the field was considered never to have had potatoes planted. This leaves 228 entries with missing data. Figure 19(A) shows the distribution of time since last potato planting where there is data. This includes intervals where potatoes have been planted but excludes intervals in the “Bare” category. Seven fields have no evidence of ever having had potatoes planted, and clearly some fields have not had potatoes for a very long time. In order to assess whether there is a difference in yield we consider any crop planted 10 or more years after the last potato crop to be free of that influence. If instances where yield is either missing, or the crop failed are excluded there are 21 instances of wheat free of potato influence and 79 instances of wheat planted where there has been a recent potato crop. The yield is significantly lower under the influence of potatoes in the rotation ($t = 3.41$ on 44.73 D.F., $p = 0.0014$) with potato influenced wheat having a mean yield of 9.13 t/ha (S.E. 0.19) compared to 10.21 t/ha (S.E. 0.25) in fields where there have been no recent potatoes (Figure 19(B)). There was no difference in the nitrogen applied or number of agrochemical applications applied to wheat crops and there is insufficient data to assess the effect of potatoes on other crops.

Figure 19. Rotational Effects –Potatoes. (A) Time since the last potato planting - the majority of intervals where there is information are within 2 years of a potato crop. Bare intervals have been excluded and there are 228 instances where the time since last potato planting is unknown. (B) Wheat yield is higher when there have been no potatoes in the rotation for at least 10 years



6.2.3. Expanded Data Set

6.2.3.1. Do Organic amendments have any effect on subsequent crop yield, agrochemical applications or nitrogen input?

There was sufficient data to examine whether there were differences in Barley, OSR, and Wheat crops planted following the application of organic amendments (see Table 52). There was no evidence of an improvement in yield following the application of organic amendments and there was no evidence of any effect in Wheat. However, there were significantly lower numbers of agro-chemical reductions in all Barley from 7.1 (S.E. 0.51) to 5.6 (S.E. 0.56) (t43 = 2.02, p=0.05) and OSR from 9.0 (S.E 0.61) to 6.5 (S.E. 0.60) (t49=2.92, p=0.005 and this was also seen in plantings for the second interval following application of organic amendments dropping from 9.6 (S.E. 0.69) to 7.5 (S.E. 0.77) (t41 = 2.08, p=0.04). This is consistent with the reduction of applications seen in potatoes above and the reduction in nitrogen applications. It was not possible to consider root vegetables because none of the onions or parsnips followed applications of organic amendments and there was no evidence of an effect two intervals after applications.

Table 52. The number of instances of crops planted in the interval following the application of organic amendments

Crop	Number of intervals	Number with yield
Barley	18	16
Cereals	3	3
Cover	9	8
Grass	1	1
Legumes	9	8
Maize	6	6
Oats	2	2
OSR	20	17
Pigs	1	1
Potatoes	21	20
Roots	16	12
Wheat	58	51

6.2.3.2. Do Cover Crops have any effect on subsequent crop yield, agrochemical applications or nitrogen input?

Although there were 49 instances of cover crops in the expanded data set, they were spread across various crops. There was no extra data for potatoes and only sufficient extra data to consider root vegetables (Table 53). However, there is a suggestion of increased yield for root crops from 53.7 t/ha (S.E. 5.1) to 80.9 t/ha (S.E.6.3) (t17=3.49, p=0.003), but also for an increase in nitrogen from 83.3 kg/ha (S.E. 8.3) where no cover crop preceded to 114.3 kg/ha (S.E. 7.0) following a cover crop so it is not clear whether the cover crop or increased nitrogen is responsible for the increase in yield.

Table 53. The number of instances of crops planted in the Interval following a cover crop

Crop	Number of intervals	Number with yield
Barley	6	6
Legumes	2	2
Maize	4	1
Oats	4	4
OSR	3	2
Potatoes	14	10
Roots	7	7
Wheat	2	2

6.2.3.3. Do livestock in the rotation have an impact on yield, nitrogen applications or agrochemical applications?

There is data on 80 fields with no livestock in them and 22 which do have livestock together with the follow-on instances of crops planted in the fields are shown in Table 54. The occurrence of livestock has no significant impact on maize, OSR, potatoes, or wheat. Barley planted in fields with livestock in the rotation had significantly fewer agrochemical application (5.3 (S.E 0.5) vs 7.0 (S.E. 0.5) (t49 = 2.62, p=0.01). For Root vegetables the presence of livestock in the rotation is associated with a significant decrease in the number of agrochemical applications from 7.2 (S.E. 0.66) to 5.2 (S.E. 0.96) (t40=-2.30, p=0.03) and a significant increase in yield from 64.9 t/ha (S.E. 3.4) to 77.9 t/ha (S.E. 4.4) (t27=2.41, p=0.02).

Table 54. Instances of crops separated by whether livestock occurs in the rotation

Crop	No livestock	With livestock
Barley	61	18
Cereals	3	0
Cover	25	26
Grass	4	21
Legumes	36	2
Maize	11	8
Oats	10	2
OSR	77	16
Pigs	0	1
Potatoes	43	14
Roots	40	20
Veg	4	1
Wheat	221	39

6.2.3.4. Is OSR in the rotation associated with differences in yield, nitrogen application or number of agrochemical applications?

Many of the fields do not have complete rotations so the absence of a record of OSR is not a guarantee that it is not part of the rotation, and these results should be treated with caution. However, Table 55 shows the number of intervals from fields with and without a record of OSR. There was no significant effect on legumes, maize, wheat. OSR in the rotation was associated with an increase in yield from 6.4 t/ha (S.E. 0.28) to 7.6 t/ha (S.E. 0.25) (t64 = 3.19, p=0.003), but also increased nitrogen application from 119 kg/ha (S.E. 7.2) to 149 kg/ha (S.E. 6.7) (t72=3.1, p=0.003) and an increase in agrochemical applications from 5.4 (S.E. 0.53) to 7.5 (S.E. 0.50) (t73 = 2.22 p=0.005). This suggests that increase may be related to differing management than the presence of OSR. There was no evidence of any difference in yield or agrochemical applications on potato crops with OSR in the rotation, but nitrogen application tended to be higher increasing from 146.8 t/ha (S.E. 15.43) to 185.9 t/ha (S.E. 10.39) (t44 = 2.14, p=0.04). In root vegetables OSR in the mixed was associated with a marginal decrease in agrochemical applications from 7.7 (S.E. 0.75) to 5.6 (S.E. 0.75) (t53=2.04, p=0.05) and increase in yield from 63.7 t/ha (S.E. 3.34) to 78.5 t/ha (S.E. 4.36) t30=2.78, p= 0.009).

Table 55. Crops in fields with and without records of oil seed rape in the rotation

Crop	Without OSR	With OSR
Barley	32	47
Cereals	0	3
Cover	24	27
Grass	17	8
Legumes	12	26
Maize	11	8
Oats	6	6
Pigs	1	0
Potatoes	25	32
Roots	39	21
Veg	4	1
Wheat	60	200

6.3. Discussion

The initial proposal had been to use a grower platform to obtain information on potentially important rotational effects and management practices which would then be tested on managed experimental farms and fed back into the platform in an ongoing process of Knowledge exchange. Gathering the data for the grower platform proved a challenge and the initial plan had to be amended. NIAB therefore undertook extensive fieldwork to obtain an initial data set including data on 55 fields from 31 growers. For each field, between five and 18 intervals were available, for a total of 630 intervals. Questionnaires were extensively quality checked and compiled into a data set which forms an anonymised resource for future analysis. The data were analysed to allow benchmarking of agricultural practices and yield by crop and to identify practices which had a significant impact on yield. These results informed the focus of the economic modelling which incorporated the data set with information on costs and crop prices to investigate the economic impact of rotational practices and interventions.

A further data set, predominantly on cereals data, was collected in conjunction with the AHDB funded soil health scorecard. Delays due to COVID-19 restrictions meant that data collection was completed shortly before the end of the grower platform project, and the analysis of the combined data sets has been used to characterise common rotational practices and feed into investigations of impacts on soil health under that project.

Key findings are that larger fields (>30 ha) tend to have lower yields per hectare than smaller fields for wheat and OSR (these are the only crops for which there is sufficient data to assess the difference). Cover crops are associated with higher yields in potato and root vegetable crops. There is no difference in yield of crops following the application of organic amendments but there are fewer agrochemical applications to succeeding barley, potato and OSR crops and lower nitrogen applications to potato crops. The only crop for which there is sufficient data to assess the impact of having potatoes in the rotation is wheat and yields are significantly lower from rotations containing potatoes. The effect of OSR in the rotation is harder to disentangle from other management practices because it is associated with increased yield in barley but also increased nitrogen and agrochemical applications. It is also associated with increased nitrogen application in potatoes. The inclusion of livestock in the rotation had little effect on most crops but was associated with fewer agrochemical applications in barley and roots, the latter also having higher yields.

It should be made clear that participants are self-selecting and the distribution of farms is not consistent across the UK, nor comprehensive so it is not possible, definitively to attribute changes in yield or inputs to field size, cover crops or organic amendments. This is very much exploratory analysis which suggests areas for further investigation. However, the platform forms a solid base of information for benchmarking, characterising management practices and investigating their implications for economic and environmental sustainability. It also demonstrates the importance of collecting longitudinal data when assessing management practices, supporting both the economic modelling as part of this project and the analysis of practices to support soil health as part of the concurrent AHDB funded Soil Biology Soil Health project.

6.4. Conclusions

- Longitudinal data on management, crop and yield data has been collected from farms across the UK and analysed to identify key features. It forms a solid base for benchmarking common practice and has fed into economic modelling and linked to soil health to identify the potential impact and efficacy of various practices. Key finding of the analysis of rotational features include:
    - Cover Crops are associated with higher yields in Potatoes.
    - The application of organic amendments is associated with a reduction in agro-chemical application in barley, OSR and potatoes and lower nitrogen application in potatoes with no corresponding loss in yield.
    - Livestock in a rotation are associated with fewer agrochemical applications in barley and root vegetables with no corresponding loss of yield in barley and in increase in yield from root vegetables.
- However, the data set is self-selecting and partial. It is not particularly large and the analysis is exploratory. These findings suggest important areas to consider for confirmatory experiments but should not be taken as in any way proven. Economic evaluation of crop rotations

6.5. Materials and Methods

The final dataset described in the section on the Grower Platform Survey (Section 6), include data on 55 fields from 31 growers. For each field, between five and 18 intervals were available, for a total of 630 intervals. This dataset was used, among others, to assess the impact of different rotation managements on the economics of the crops considered. To do so, for the crops with a sufficient number of observations and enough information on related practices, researchers assigned prices to inputs, outputs and farm operations and calculated the resulting costs, earnings, and gross margins. Differences in these variables depending on previous management decisions (e.g., application of amendments) could then be assessed. Although this was not a controlled environment and, therefore, there could be omitted variables affecting the results (e.g., farm management, soil quality, weather, cultivar, etc.).

The rotation dataset includes data on 55 fields (of which one, was a split field in 2015), belonging to 31 owners. For each field, between five and 18 intervals are available, the oldest one starting in September 2004, and the most recent one ending in July 2018. Overall, 630 intervals are available. The intervals were classified into 12 crop categories, including “bare soil” (218 intervals), cover crops (21), and grassland (8).

Prices were assigned to each input, output, and farm operation (mechanisation service) in the intervals for which the respondent provided enough detail. This, in turn, allowed the implementation of an economic analysis of rotations for the crops with a large enough number of intervals available. These crops include potatoes (56 intervals), barley (46 intervals), oilseed rape (44 intervals), and wheat (138 intervals). The economic analysis consists of comparing costs and gross margins using the pooled panel dataset, with a focus on the impact of cover crops and organic amendments (hereafter, OAs).

Most of the prices (costs) used in the analysis are from the Farm Management Handbook 2018/2019 (SAC Consulting, 2018) and are based on projected prices for the year ahead, set in summer 2018. Assigning prices from the same year (2018) to intervals from different years allowed the removal of additional variability due to price fluctuations, and thus to compare gross margins for long-term rotations. For nutrients, OAs and irrigation, the rate of application was available in the survey, and was multiplied by the price. The cost of OAs was obtained from the questionnaires, by averaging the prices declared for the same amendment by different respondents. For different typologies of farm operations, including sprays, the number of occurrences during each interval was available. Each occurrence was assigned a price equal to the average cost charged by a contractor for implementing that operation – in case of bias, the bias goes in the same direction for all observations; therefore, the results remain valid. Detailed prices are provided below for each crop for which each price typology was used. Table 56 reports costs which vary for each crop, for the crops incurring the cost at least once.

Table 56. Prices for the economic analysis: inputs and operations whose prices vary depending on the crop

Type of input / operation	Bare soil	Barley	Cover	Grassland	Legumes	Maize
Seeds		78.85	47.49	22.00	105.00	172.50
Irrigation		4.94				
Molluscicide						
Insecticide		4.25			3.70	
Herbicide					12.00	
Amendment application [1]	33.15	39.48 / 33.15	39.48	39.48		33.15
Direct drill into stubble			52.85			
Non-inversion tillage deep	64.37		64.37		40.08	40.08
Drill/plant (incl. fuel)			36.92	39.75	58.62	67.41
Harvesting (incl. fuel)		95.63	68.64	115.48	106.45	174.25
Single pass drilling			56.83			
Plant/drill (incl. fuel)			75.34		58.62	67.41
Selling price	-	145.00	-	-	200.00	

Type of input / operation	Oats	OSR	Potatoes	Roots	Vegetables	Wheat
Seed (per hectare) [2]	79.80	49.50	720.00	200.00	1,140.00	94.60
			1,400.00	47.00		92.00
			1,728.00	21.00		
Irrigation (ha.mm)			7.15	4.94		4.94
Molluscicide		7.50				7.70
Insecticide		4.25				3.70
Herbicide		19.48				28.23
Amendment application [1]		39.48	39.48 / 33.15	39.48		39.48
Direct drill into stubble		52.42		64.25		
Non-inversion tillage deep	40.08	40.08		40.08	40.08	40.08
Drill/plant (incl. fuel)	60.20	62.60	150.63	66.58	54.94	43.65
Harvesting (incl. fuel)	95.63	96.16	488.66		390.75	95.63
Single pass drilling				52.85		
Plant/drill (incl. fuel)	60.20	62.60	150.63			43.65
Selling price [3]	155.00	325.00	119.20	-	700.00	165.00
			176.06			
			232.07			

Notes: Seed costs are reported per hectare; spay costs per application; operation costs per occurrence; selling prices per ton. [1] £33.15 for slurry, £39.48 for other amendments (rear discharge, medium). [2] £720 for potato maincrop (49 intervals), £1,400 for potato salad (4 intervals), £1,728 for potato seeds (3 intervals); £21 for turnips, £47 for forage swedes, £200 for fodder beet; £94.60 for spring wheat, £92 for winter wheat; [3] £119.20 for potato (maincrop), £232.07 for potato (salad), £176.06 for potato (seeds).

6.5.1. Fertilisers and other applications (with no variation depending on the crop)

The following costs for fertilisers, agrochemicals and organic amendments were used in the analysis.

N: £0.67/kg; P_2O_5: £0.68/kg; K_2O: £0.45/kg

Nematicide: NA; Molluscicide: NA; Insecticide: NA; PGR: NA; Herbicide: NA; Fungicide: £17.75

Spraying (for each agrochemical application): £13.36 + £1.14 (fuel) = £14.50/ha

Organic manure: FYM cattle £6.00/t; FYM pig £25.00/t; Poultry manure: £31.22/t; Slurry pig: £12.00/t; Compost green waste £6.17/t; Digestate separated liquor/fibre £1.50/t

6.5.2. Farm operations (with no variation depending on the crop)

The following cost for tillage were used in the analysis

Bed tilling: £137.14

Broadcasting: £25.67

Destoning: £236.86

Direct drill into stubble: £52.85

Non-inversion tillage shallow: £50.72

Ploughing: £72.70

Ploughing with press: £79.40

Rotovating: £66.81/ha

Subsoiling: £76.55/ha

Fertiliser application: £14.38/ha

N.B.: Fuel consumption is included for the operations for which it was specified in the Farm Management Handbook 2018/2019.

6.5.3. Gross margin

The gross margins mf,t are calculated per hectare, for each field f and interval t, by subtracting (1) the costs c from (2) the earnings e: m_(f,t)=e_(f,t)-c_(f,t).

(1) The costs c are obtained by summing up the costs of seeds, agrochemicals (fertilisers and pesticides), irrigation, manure, and farm operations: $c_{f,t} = \text{seeds}\left(\frac{\text{£}}{\text{ha}}\right) + \sum \text{nutrients}\ (\frac{\text{£}}{\text{kg}}) * \text{rate}\ (\frac{\text{kg}}{\text{ha}}) + \text{irrigation}\left(\frac{\text{£}}{\text{ha}}\right) + \sum \text{pesticides}\left(\frac{\text{£}}{n_{apply}}\right) * n_{apply} + \sum \text{manure}\left(\frac{\text{£}}{\text{t}}\right) * \text{rate}\left(\frac{\text{t}}{\text{ha}}\right) + \sum \left[\text{farm operation}\left(\frac{\text{£}}{n_{apply}}\right) + \text{fuel}\left(\frac{\text{£}}{n_{apply}}\right)\right] * n_{apply}$

For appreciating the benefits of cover crop and/or of OAs, we calculated the cumulated gross margins along more than one growing season, including the current crop interval and the interval in which the cover crop was established or the OAs applied (plus the bare soil interval in the middle, if reported by the respondent). The formula is $cgm_{f,t} = m_{f,t} + m_{f,t-1}$ in the absence of the intermediate bare soil interval, and $cgm_{f,t} = m_{f,t} + m_{f,t-1} + m_{f,t-2}$ in its presence.

6.6. Results

6.6.1. Typologies of rotations

As a first step, using Markov chains we calculated, for each crop typology, the probability of it being followed or preceded by each of the other crop typologies. As shown in Table 57, the most frequent interval was “bare soil”, with an overall probability of 34.6% (note: not all growers indicated the bare soil intervals; therefore, these results need to be considered carefully). Wheat had a probability of 22.0%, potatoes of 8.9%, root vegetables of 7.3%, barley of 7.1%, and oats of 7.0 %, other crops where less frequent. Barley was followed by bare soil with probability of almost two thirds, and by oats or roots with probabilities of 8.7% each. Oilseed rape was almost always followed by bare soil (87.5%), but by wheat otherwise. Potatoes were followed by wheat with probability 54.6%, and by bare soil with probability 32.7%. Wheat was followed by bare soil with probability 61.6%, otherwise by oats (11.6%).

Table 57. Probability of observing the crop in the column if the crop in the row was observed in the previous year.

Year t+1 → Year t ↓	Bare soil	Barley	Cover crops	Grassland	Legumes	Maize	Oilseed rape	Oats	Potatoes	Roots	Vegetables	Wheat
Bare soil	0.014	0.128	0.005	0.028	0.005	0.064	0.028	0.096	0.142	0.138	0.037	0.317
Barley	0.652	0.044	0.044				0.022	0.087	0.022	0.087		0.044
Cover crops	0.286			0.095		0.048	0.048		0.429	0.095		
Grassland	0.333			0.067					0.067			0.533
Legumes	0.125	0.125			0.500			0.125				0.125
Maize	0.556		0.278								0.056	0.111
Oilseed rape	0.875											0.125
Oats	0.705	0.023	0.023						0.046			0.205
Potatoes	0.327				0.018	0.018		0.036	0.036	0.018		0.546
Roots	0.304	0.109	0.044	0.109		0.022			0.065	0.087	0.022	0.239
Vegetables	0.667								0.083	0.083	0.167	
Wheat	0.616	0.058	0.073	0.007	0.015	0.007		0.116	0.044	0.029		0.036
Total incidence	0.346	0.071	0.033	0.024	0.013	0.029	0.013	0.070	0.089	0.073	0.019	0.220

If, instead, we focus on the crop typologies preceding other crop typologies (Table 58), we observe that barley was preceded by bare soil with probability 26.4%, by legumes with probability 25.7%, and by root vegetables with probability 22.4%. Oilseed rape was preceded by cover crops with probability 49.2%, by bare soil with probability 28.4%, and by barley with probability 22.4%. Potatoes were preceded by cover crops with probability 45.9%, and by bare soil with probability 15.2%. Finally, wheat was preceded by potatoes with probability 23.9%, grassland with probability 23.4%, bare soil with probability 13.9%, and root vegetables (10.5%).

Table 58. Probability of having observed the crop in the row if observing the crop in the column

Year t+1 → Year t ↓	Bare soil	Barley	Cover crops	Grassland	Legumes	Maize	Oilseed rape	Oats	Potatoes	Roots	Vegetables	Wheat
Bare soil	0.003	0.264	0.010	0.090	0.009	0.404	0.284	0.209	0.152	0.256	0.131	0.139
Barley	0.119	0.089	0.094				0.224	0.189	0.023	0.162		0.019
Cover crops	0.052			0.312		0.300	0.492		0.459	0.177		
Grassland	0.061			0.218					0.071			0.234
Legumes	0.023	0.257			0.931			0.271				0.055
Maize	0.102		0.598								0.198	0.049
Oilseed rape	0.160											0.055
Oats	0.129	0.047	0.049						0.049			0.090
Potatoes	0.060				0.034	0.115		0.079	0.039	0.034		0.239
Roots	0.056	0.224	0.094	0.356		0.137			0.070	0.162	0.077	0.105
Vegetables	0.122								0.089	0.155	0.594	
Wheat	0.113	0.119	0.156	0.024	0.027	0.045		0.252	0.047	0.054		0.016

6.6.2. Gross margins

Using the method detailed in the Method section, earnings, costs, and gross margins were calculated. These are reported only for the crops which presented a large enough number of intervals, and which represent a compact enough category (e.g., we did not have enough information to calculate gross margins for vegetables). The gross margins range from an average of £2,715 for potatoes, to £808 for wheat, £543 for barley, and £508 for oilseed rape. The margins for the intervals with bare soil (which also includes stubble following cereals) and with cover crops are negative because respondents included the costs of farm operations but sold no products. Nevertheless, these are reported in Table 59 as they are used to calculate the economic benefits of cover crops and farm amendments along years. The growers incurred in average cost of £48 when the soil was left bare, and £214 if they were establishing a cover crop (whose typology is unknown).

Table 59. Earnings, costs and gross margins for the main crop categories

Crop	Intervals	Earnings		Costs		Gross margin	
		Mean	St. dev.	Mean	St. dev.	Mean	St. dev.
Bare soil	218	0.00	0.00	47.70	97.23	-47.70	97.23
Barley	46	1,035.69	271.34	493.03	132.54	542.66	230.09
Cover crop	21	0.00	0.00	214.45	88.87	-214.45	88.87
Oilseed rape	44	1,199.91	439.51	691.63	189.45	508.28	348.16
Potatoes	56	5,772.92	1,620.92	3,058.15	2,891.15	2,714.78	3,390.36
Wheat	138	1,521.18	436.53	713.43	156.60	807.75	449.35

6.6.3. Profitability of growing cover crops before potatoes

A first analysis focused on the profitability of growing cover crops before potatoes as shown by the gross margins of potatoes after cover crops and after bare soil, respectively. Potatoes are the only crop for which the sample size is large enough to test the impact of cover crops. The results need to be considered carefully due to sample size issues and potential confounding effects as well as the use of average prices given limited details of on farm operations. A dummy variable was created to indicate whether potatoes were preceded either by "bare soil" or by cover crops (potentially followed by a bare soil interval). All the instances where bare soil intervals were not indicated (three in which potatoes were preceded by wheat, one by cauliflowers) and two in which potatoes were preceded respectively by stubble turnips and "forage swedes & turnips" were excluded from the analysis because the cost of soil management operations for the previous intervals could not be calculated or was not directly comparable. Moreover, if we included the cases when potatoes were preceded by a catch crop, the interpretation of the results would become much more complex, since the opportunity cost of the most profitable (alternative) soil use to cover crops and bare soil needed to be identified. The cases of missing yields were also excluded. As a result, out of 56 intervals of potatoes (of which 10 were in the first interval, which therefore could not be used in the analysis), there were 14 instances of cover crops (possibly with a bare soil interval in the middle), and 28 of bare soil (no cover crop) proceeding potatoes.

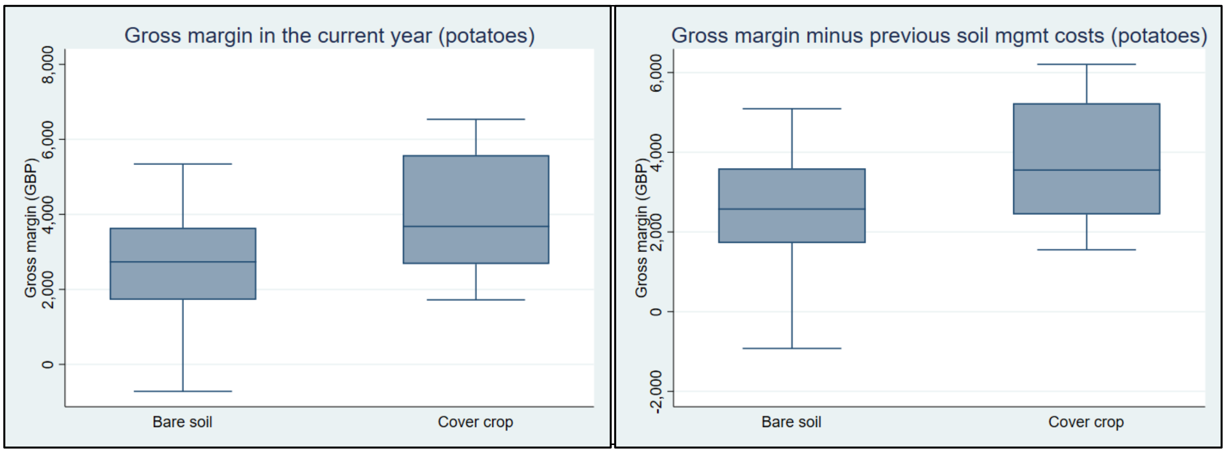
The gross margin per hectare was calculated as the difference between price times yield, and the cost of variable inputs, amendments, and field operations (including fuel costs). The cost of the operations is the average cost of hiring a contractor for doing a specific piece of work. The numbers of agrochemical applications (13.3 after bare soil, and 15.0 after cover crops, p = 0.193), and of field operations (6.9 and 6.6, p = 0.330) do not differ significantly. The "net margin" (Table 60) is the gross margin minus land management costs in the previous interval (i.e., the costs of operations implemented on bare soil, or of managing the cover crops). If the bare soil is preceded by a cover crop, the costs of the two previous intervals are both subtracted, thus the "net margin" represents the difference between the earning from selling the yield and all the farm costs incurred since harvesting the last crop in the previous summer (mostly in August).

Table 60. Compared potato yields and gross margins after cover crops and bare soil, including net of costs

Variables	Bare soil		Cover crop		Difference		*p*-value
	Mean	St. dev.	Mean	St. dev.	Mean	St. dev.	
Yield (t/ha)	41.46	1.87	54.79	2.64	-13.32	3.24	0.0001
Expected yield (t/ha)	41.89	1.77	51.00	1.03	-9.11	2.62	0.0006
Actual – expected (t/ha)	-0.12	1.30	3.79	2.32	-3.91	2.46	0.0602
Gross margin (£)	2,685.49	246.30	4,039.92	449.60	-1,356.43	470.52	0.0032
Net margin (£)	2,624.73	272.17	3,771.00	423.02	-1,146.27	480.39	0.0112

The average yield is significantly higher after cover crops (54.8 t/ha) than after bare soil (41.5 t/ha). The gross margin is also significantly higher (£4,040 *vs* £2,685 per hectare). The difference is due to the higher yield after cover crops, which results in significantly higher earnings (£6,531 *vs* £5,541, p = 0.015). The costs in the current interval are also different but they are higher after bare soil (£2,857 *vs* £2,491), but the difference is not statistically significant (p = 0.163). Even if the difference between gross margins is smaller when the costs of establishing the cover crop in the previous interval are considered (£3,771 *vs* £2,624), this is still significantly in favour of the use of cover crops (*p* = 0.011). These figures are particularly relevant because, even if growers are aware of the benefits of cover crops (they expect a yield of 51.0 t/ha *vs* 41.9 t/ha on average), they seem to underestimate them: while the gap between the actual and expected yield is not significantly different from zero after bare soil, this gap amounts to 3.8 t/ha on average after cover crops. Box plots of the gross margin in the current year and of the gross margins minus soil management costs in the previous interval, after bare soil and after cover crops respectively, are illustrated in Figure 20.

Figure 20. Potato gross margins after bare soil and after cover crops, including net of soil management costs



6.6.4. Organic amendments: overview

A second analysis focused on the economics of organic amendments (OAs). For the sake of this analysis (1) the *current* interval is defined as including the bare soil interval that precedes the current crop, if available; (2) the *previous* interval indicates the last interval with a crop, plus the preceding bare soil interval, if available. Overall, the dataset includes 85 intervals with OAs applied at least once, and 11 intervals where OAs were applied twice. The most common OA type was poultry manure (34 occurrences), followed by cattle farm yard manure (25), digestate separate liquor (13), compost green waste (nine) and pig slurry (four). Other OA types appear less frequently. A cross-tabulation of OA application by interval and crop type is provided in Table 61.

Overall, five issues concerning OAs were investigated for the crop categories with the largest number of occurrences (barley, oilseed rape, potatoes, and wheat):

1. If OAs and chemical fertilisers are substitutes or complements
2. The cost of nutrients for different composition between organic and chemical
3. The rate and the cost of applications of chemical fertilisers after OAs
4. The yields and gross margins with and without OAs
5. Some considerations on the joint impact of amendments and cover crops on potato

Table 61. Application of organic amendments (OAs) in the current and previous interval, by crop category.

Crop category	No OA [1]	OA in the current interval [1]	OA in the previous interval	OA in both intervals
Barley	33	6	6	1
Cover crop	13	6	2	0
Forage maize	6	6	2	1
Grassland	6	1	0	1
Legumes	17	0	1	0
Oats	6	0	1	1
Oilseed rape	32	9	1	2
Potato	25	21	7	3
Root vegetables	28	14	3	1
Vegetables	12	0	0	0
Wheat	103	5	25	5

Note: [1] Including 44 and 13 intervals with no observations for the previous interval.

6.6.4.1. Complements or substitutes

To assess if OAs and chemical fertilisers were used as complements or substitutes, nutrient content (NKP) was assigned to each OA type based on data from the *Farm Management Handbook 2018/2019* (SAC Consulting, 2018, p. 5). The residual N and P (“credit”), to be used in subsequent years, was also calculated according to the following proportions: 1/5 of N from organic manure after one growing season, and 1/10 after two seasons; 1/2 of P from all fertilisers and manures after one growing season, 1/4 after two seasons, and 1/8 after three seasons. For each crop, the correlation between the number of applications of OAs and of chemicals, and between NKP rates from both OAs and chemical fertilisers in the *current* interval were calculated and are reported in Table 62. If OAs and chemical amendments are substitutes, we should observe a negative and significant correlation, while if they are complements, the correlation should be positive. We observe no significant substitution or complement effect between the number of applications of OAs and chemical fertilisers. However, there is a weak substitution effect (correlation below 0.5) when nutrient content is considered. This is significant in the case of K (-0.270) and N (-0.432) for barley, and in the case of P (-0.441) and K (-0.343) for potatoes. In no instance are the rate of nutrients from OAs and chemical fertilisers are complements. When controlling for the N and P “credit” (i.e., when these credits are included as covariates in a regression model), P from chemicals is found to be substitute of P from OAs for barley (-0.133) and oilseed rape (-0.232). Further analyses showed that the number of chemical applications was significantly lower in the presence of higher N residuals.

Table 62. Correlation between number of applications of chemicals and of OAs, and between the rate of N, K and P from OAs and from chemicals.

Correlation	Barley	Oilseed rape	Potatoes	Wheat
Applications (no.)	-0.227	0.071	0.215	-0.017
P (kg/ha)	-0.156 (-0.133*)	-0.216 (-0.232***)	-0.441***	-0.039
K (kg/ha)	-0.270*	-0.182	-0.343***	0.016
N (kg/ha)	-0.432***	-0.114	-0.188	0.019

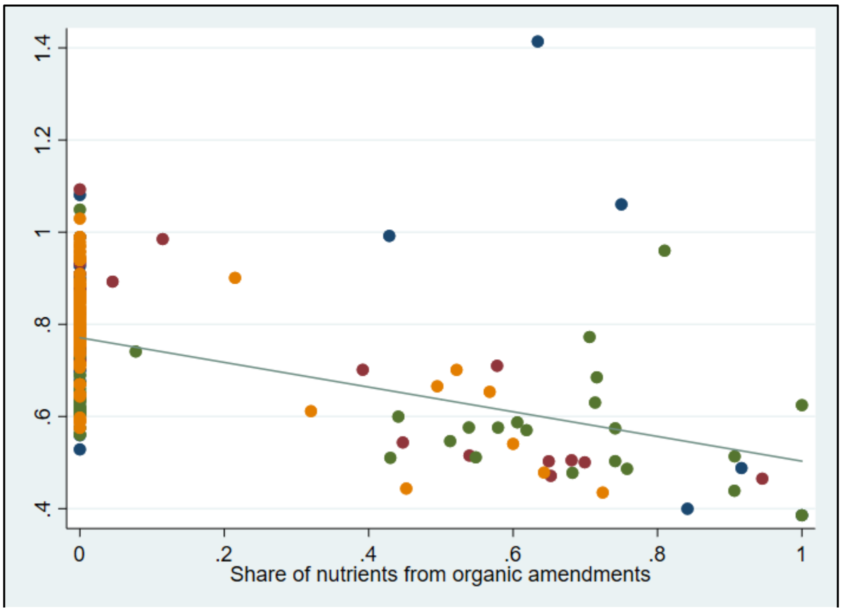
6.6.4.2. Nutrient costs for different compositions

Using data from the above analysis and the price of farm operations calculated from the *Farm Management Handbook 2018/2019* (SAC Consulting, 2018), the total cost of fertilising was obtained by summing the costs of OAs, chemical fertilisers, and their application. The average cost of soil fertilisation was £190 for barley, £224 for oilseed rape, £407 for potatoes, and £223 for wheat. The unitary (kg) costs of N, K and P separately, and of NKP overall were also calculated for these four crops and correlated with the share of nutrients obtained from OAs (from 0 to 1). The correlation coefficients are provided in Table 63, and the share is plotted against the unitary cost on NKP in Figure 21. In 61 crop intervals we observe combinations of OAs and chemical fertilisers. A larger share of nutrients from OAs is related to a lower unitary cost of NKP overall for oilseed rape (-0.729), potatoes (-0.372), and wheat (-0.518), but not for barley. This negative correlation is also significant for the unitary cost of N separately, being maximum for potatoes (-0.419); the coefficient is even larger if the N “credit” is included (-0.613). Only the unitary cost of P for wheat increases when a larger share comes from OAs, but this is only marginally significant.

Table 63. Correlations between the share of nutrients obtained from OAs and the unit cost of fertilising, for each nutrient or group of them

Nutrients	Barley	Oilseeds	Potato	Wheat
P (kg/ha)	0.354	0.275	-0.141	0.257*
K (kg/ha)	0.133	0.043	0.062	-0.048
N (kg/ha)	0.127	-0.289*	-0.419***	-0.187**
P with credit (kg/ha)	0.097	-0.078	-0.152	0.242*
N with credit (kg/ha)	0.018	-0.528***	-0.613***	-0.316***
NKP (kg/ha)	-0.168	-0.729***	-0.372***	-0.518***

Figure 21. Correlation between the share of nutrients obtained from OAs (0-1) and the unitary cost of nutrients (£/kg) for barley, oilseed rape, potato, and wheat.



6.6.4.3. Land management costs after organic amendments

For the four crop categories for which there was a large enough number of intervals available in the dataset (barley, oilseed rape, potatoes, and wheat), we calculated whether there was a significant difference in key economic and agronomic variables depending on application of OAs in the current (Table 64), or previous interval (Table 65). The variables considered include fertilising costs (also discussed above), total costs, number of agrochemical applications, and number of field operations. The *total* cost of fertilisation (different from the *unitary* cost considered above) is significantly higher for all crops considered when OAs were applied in the *current* interval compared to when no OAs were applied (e.g., £502 *vs* £337 for potatoes). This same cost does not differ significantly if application of OAs in the *previous* interval is used as a criterion. Such results must be considered carefully because the rates of application can differ significantly between fields. Instead, the total costs incurred during an interval (which also include the costs of pesticides, irrigation, field operations, etc.) do not differ significantly depending on application of OAs, meaning that, overall, the cost of fertilisation is small compared to other costs, especially for potatoes.

The number of agrochemical applications was significantly higher in case of no application of amendments in the current interval for barley (2.3 *vs* 0.9, *p* = 0.002) and in the previous interval for wheat (3.1 *vs* 2.1, *p* = 0.000), but not for oilseed rape and for potatoes. Finally, the number of field operations was significantly lower when OAs were applied in the current interval for barley (3.6 *vs* 5.6, *p* = 0.003). For wheat, the number was significantly higher if amendments were applied in the current interval (7.5 *vs* 6.1, *p* = 0.017), but significantly lower when OAs were applied in the previous interval (5.7 *vs* 6.4, *p* = 0.092). These results suggest that fertilising costs are higher with OAs because farmers apply more units of nutrients than they would apply with chemical fertilisers, but this does not affect total costs significantly, and the number of other field operations tends to decrease for cereals (barley and wheat) instead.

Table 64. Statistical tests for the difference in key variables (fertilising costs, total costs, agrochemical applications and field operations) with and without application of OAs in the current interval.

Variable	Sub-groups	Barley	Oilseeds	Potato	Wheat
Fertilising costs (£)	Amendments	316.36	292.91	502.04	355.13
	No amendments	167.53	201.43	336.51	213.03
	t-test ≠	0.000	0.000	0.002	0.000
Total costs (£)	Amendments	438.17	726.52	3,428.04	791.37
	No amendments	502.88	680.00	2,780.72	707.34
	t-test ≠	0.239	0.487	0.412	0.102
No. agrochemical applications	Amendments	0.86	2.09	1.67	2.80
	No amendments	2.33	2.61	2.22	2.90
	t-test ≠	0.002	0.320	0.100	0.823
No. field operations	Amendments	3.57	6.00	6.50	7.50
	No amendments	5.64	5.73	6.78	6.13
	t-test ≠	0.003	0.687	0.677	0.017

Table 65. Statistical tests for the difference in key variables (fertilising costs, total costs, agrochemical applications and field operations) with and without application of OAs in the previous interval.

Variable	Sub-groups	Barley	Oilseeds	Potato	Wheat
Fertilising costs (£)	Amendments	164.53	230.09	366.79	213.38
	No amendments	202.70	221.09	436.15	226.88
	t-test ≠	0.376	0.867	0.350	0.489
Total costs (£)	Amendments	448.76	552.79	2,415.54	701.79
	No amendments	509.71	693.61	2,772.06	705.34
	t-test ≠	0.274	0.247	0.233	0.917
No. agrochemical applications	Amendments	1.57	2.33	1.80	2.07
	No amendments	2.29	2.40	2.06	3.14
	t-test ≠	0.149	0.940	0.572	0.000
No. field operations	Amendments	5.43	5.33	7.00	5.70
	No amendments	5.34	5.80	6.44	6.35
	t-test ≠	0.905	0.701	0.563	0.092

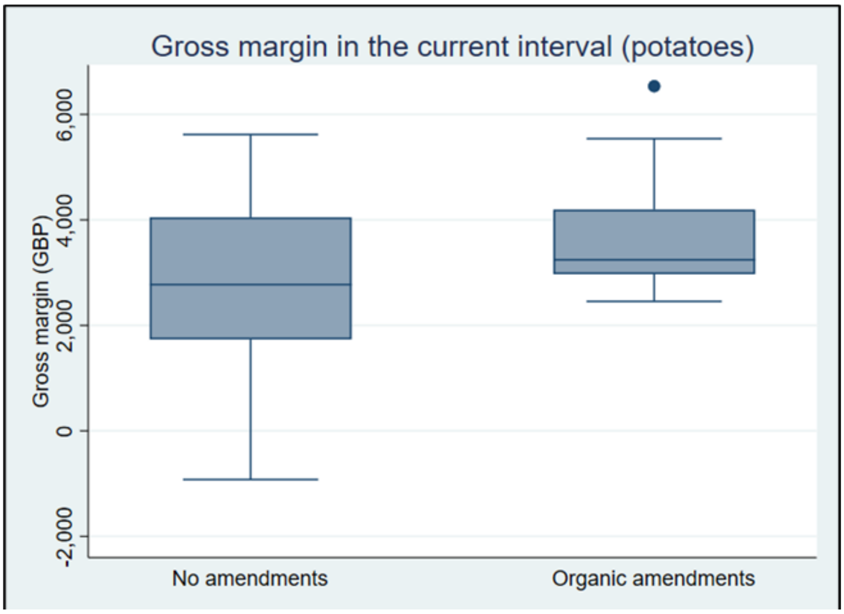
6.6.4.4. Gross margins with and without organic amendments

After focusing on the costs and on the number of agrochemical applications and field operations, we assessed, for the same four crops (barley, oilseed rape, potatoes, and wheat), if the gross margins in the *current* interval differed significantly depending on application of OAs either in the current or in the previous interval. The gross margins, presented in Table 66, are calculated net of soil management costs in the previous bare soil interval, if present. We found no significant positive impact on gross margins of applying OAs in the *current* interval (however, the gross margin for potatoes was marginally higher if no OAs were applied: £3,403.00 *vs* £2,140.77, $p = 0.083$ in a monodirectional t-test for OA < no OA). In turn, the gross margin for potatoes (box plots shown in Figure 22 is higher in the case of application of OAs in the *previous* interval compared to the case of no application (£3,782.92 *vs* £2,975.35, $p = 0.071$). Such results are driven by yields, which were significantly higher when OAs were applied in the previous interval (52.1 t/ha *vs* 45.0 t/ha, $p = 0.045$), and significantly lower when amendments were applied in the current interval (43.6 t/ha *vs* 50.1 t/ha, $p = 0.019$). For barley, previous OA application resulted in lower margins (£386.12 *vs* £588.37, $p = 0.010$ in a monodirectional t-test for OA < no OA), likely due to significantly lower yields (5.4 t/ha *vs* 7.1 t/ha, $p = 0.002$). ANOVA tests showed no significant joint impact of manure application in the current and in previous interval on gross margins for the crops considered. Of course, these results should be considered carefully due to the small sample sizes and omitted variables.

Table 66. Difference in gross margins with and without organic amendment application (current and previous interval)

Gross margin (£)	Barley	Oilseeds	Potato	Wheat
Current amendments	646.32	533.02	2,140.77	808.65
No amendments	541.70	514.57	3,403.00	856.71
t-test (OA > no OA)	0.108	0.436	0.917	0.664
Previous amendments	386.12	476.99	3,782.92	848.17
No amendments	588.37	502.07	2,975.35	873.73
t-test (OA > no OA)	0.995	0.540	0.071	0.637

Figure 22. Potato gross margins with and without the application of OAs in the previous interval.



6.6.4.5. *Organic amendments and cover crops*

As a final step, we cross tabulated the gross margins for potatoes with and without the application of OAs and with and without the use of cover crops. Potatoes are the only crop for which there are enough observations. The margins are calculated net of soil management costs in the previous bare soil interval if present. The numbers are small: 28 instances of "bare soil", 14 of cover crops, nine of OAs in the previous interval, and 17 of OAs in the current one. The gross margins are shown in Table 67 and range from a maximum of £4,029.82 on average with OAs and cover crops in the previous interval, to a minimum of £2,549.43 with bare soil and no OAs. However, ANOVA tests found no significant impact on yields and gross margins of current or past application of OAs: only the impact of cover crops was marginally significant ($p = 0.099$). Nevertheless, gross margins conditional on cover crops are higher when OAs are applied.

Table 67. Cross tabulation of potato gross margins with/without cover crops, and with/without OAs (previous and current interval)

Previous application		Bare soil	Cover crops	Total
Without amendments	Gross margin	2,549.43	3,970.29	2,893.88
	St. Dev.	1,332.90	1,717.63	1,536.29
	no.	25	8	33
With organic amendments	Gross margin	3,470.93	4,029.82	3,843.52
	St. Dev.	640.84	1,672.43	1,388.85
	no.	3	6	9
Total	Gross margin	2,648.16	3,995.80	3,097.38
	St. Dev.	1,301.49	1632.58	1,540.78
	no.	28	14	42

Current application		Bare soil	Cover crops	Total
Without amendments	Gross margin	2,644.29	3,877.05	3,285.33
	St. Dev.	935.85	1,635.09	1,460.58
	no.	12	13	25
With organic amendments	Gross margin	2,651.07	5,539.57	2,820.98
	St. Dev.	1,551.35	-	1,657.43
	no.	16	1	17
Total	Gross margin	2,648.16	3,995.80	3,097.38
	St. Dev.	1,301.49	1,632.58	1,540.78
	no.	28	14	42

6.6.5. Field size and gross margins

We have also tested whether gross margins differ significantly depending on field size. Fields were classified as “small” if their size was below the median area for that specific crop, and “large” otherwise. T-tests were used to assess if the gross margins differed significantly. A large enough number of intervals to test the effect of field size was available for barley (45 usable intervals), oilseed rape (40), potatoes (53), and wheat (132). Box plots for each crop and for “small” and “large” fields separately are provided in Figure 23. Overall, we found that smaller fields show significantly higher gross margins per hectare for all the crops considered; for barley and potatoes, costs were significantly higher in larger fields. Number are as follows:

For barley, the margins were £613 for small fields and £512 for large fields ($p = 0.041$); the costs were £459 and £534, respectively ($p = 0.027$);

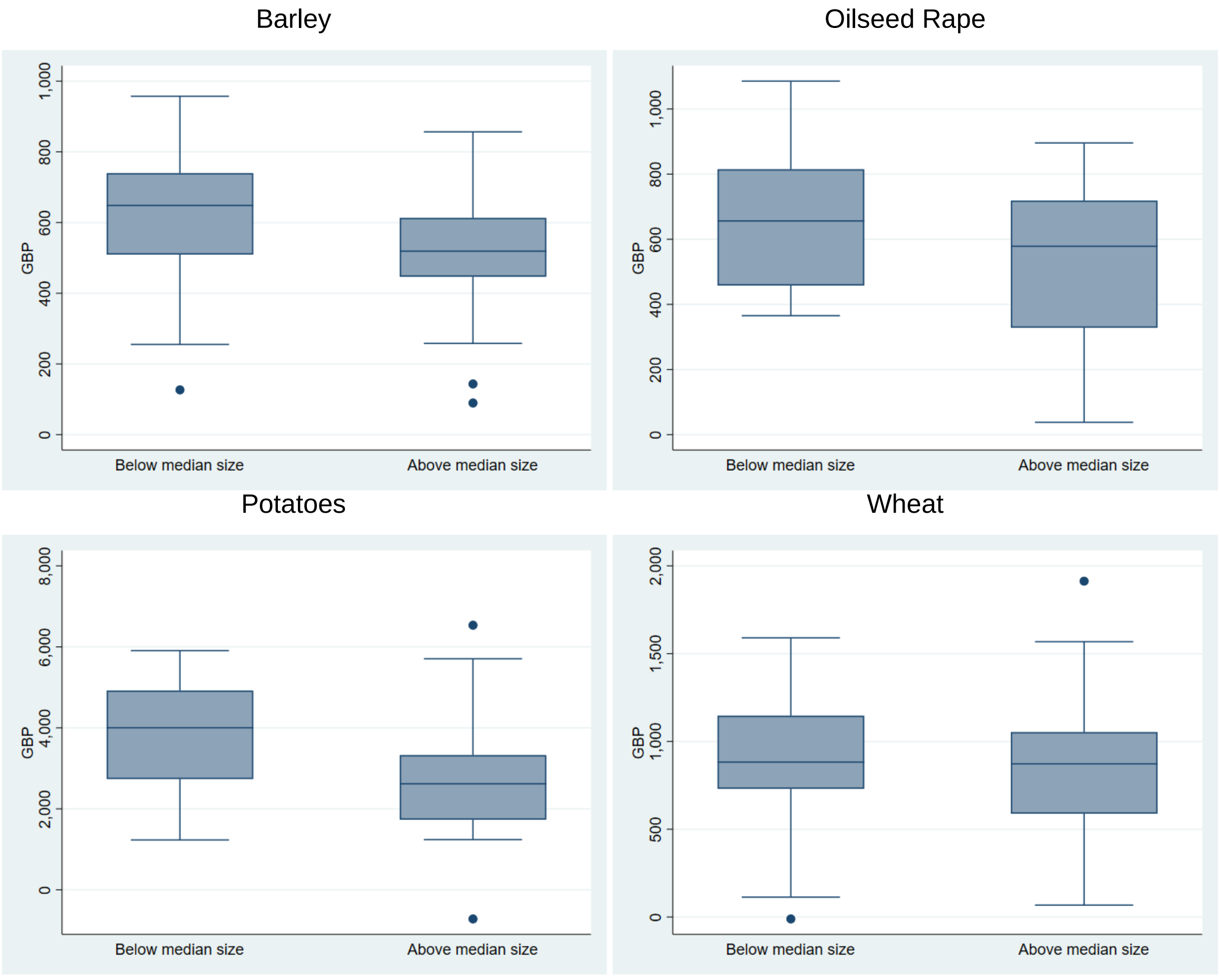
For oilseed rape, the margins were £656 for small fields and £515 for large fields ($p = 0.032$); the costs were £718 and £745, respectively ($p = 0.281$);

For potatoes, the margins were £3,817 for small fields and £2,756 for large fields ($p = 0.004$); the costs were £2,422 and £3,001, respectively ($p = 0.002$);

For wheat, the margins were £916 for small fields and £827 for large fields (*p* = 0.064); the costs were £711 and £727, respectively (p = 0.247).

The number of fertiliser applications and of field operations did not differ significantly depending on field sizes for any of the four crops considered.

Figure 23. Gross margins in fields of size above and below the median size of the dataset.



6.6.6. A final focus on expected yields

Our rotation dataset does not allow us to consider the impact on yields of soil, climate, different farm management practices, and of other field-specific characteristics. However, expected yields embed growers' knowledge of these conditions, plus their beliefs about the impact of specific treatments that they have implemented (e.g., OAs, cover crops, etc.). Therefore, the gap between actual and expected yields provides an overview of the benefits of the treatments compared to their baseline expectations. Through statistical analysis of expected and actual yields (both available in the dataset), we found that barley yields are slightly underestimated when OAs are applied in the current interval (by 0.12 t/ha) and overestimated without amendments (by 0.60 t/ha); this difference is statically significant (*p* = 0.042). Furthermore, potato yields are underestimated after cover crops (-3.79 t/ha) and slightly overestimated after bare soil (0.12 t/ha). This difference is statistically significant (*p* = 0.060), suggesting that there is limited awareness of the benefits of cover crops. Since economic decisions are based on expectations, having correct expectations about yields in the presence of treatments is key to make the right decisions.

6.7. Discussion

Using the dataset of farm rotations across the UK, we assessed the economic impact of different management practices in terms of gross margins. In particular, we focused on cover crops and organic amendments. Although this was a non-controlled environment and therefore the results need to be considered carefully, some relevant patterns emerged.

Four crops presented enough observations to draw meaningful conclusions: potatoes, barley, oilseed rape, and wheat. The estimated gross margins ranged from an average of £2,715 for potatoes, to £808 for wheat, £543 for barley, and £508 for oilseed rape.

Cover crops were usually grown before potatoes or oilseeds. However, only for potatoes did we have enough observations to assess their impact. We found that the average potato yield is higher after cover crops than after bare soil, while the difference in costs is not significant. Consequently, the gross margin is significantly higher after cover crops, and remains as such (£3,771 *vs* £2,624) even after subtracting the costs of establishing the cover crop in the previous interval. Respondent growers underestimated (predicted) potato yields after cover crops.

The economic impacts of applying organic amendments (OA) are less clear-cut. Overall, the dataset included 85 intervals with OAs applied at least once; the most common is poultry manure, followed by cattle farm yard manure. OAs and chemical fertilisers seem to be used as substitutes, although the substitution effect is weak and only significant for barley and potatoes. Second, obtaining a larger share of nutrients from OAs was related to a lower *unitary* cost of nutrients for oilseed rape, potatoes, and wheat, but to a higher *total* cost of fertilisation per hectare for all crops (although with different rates of application). Instead, the total costs incurred during an interval did not differ significantly in case of OA application because the number of agrochemical applications was lower for most crops. Finally, we found no significant impact on gross margins of applying OAs in the current or previous interval, except for potatoes, whose gross margin was higher in the case of OA application in the previous interval due to higher yields.

Related to field size, we found that in small fields the gross margins per hectare are significantly higher for all the crops considered, and the costs are significantly lower for barley and potatoes.

These results suggest that specific rotation management practices which benefit the environment by improving soil health, namely the use of cover crops and organic amendments, do not necessarily compromise economic sustainability. The additional costs of establishing a cover crop before potatoes do not seem to offset the yield benefits, and the use of OAs does not increase costs significantly. Since these results are not based on experiments, further research is needed to verify if they hold when controlling for other variables. Nevertheless, they provide valuable preliminary insights into the economics of cover crops and OAs in a rotation environment.

6.8. Conclusions

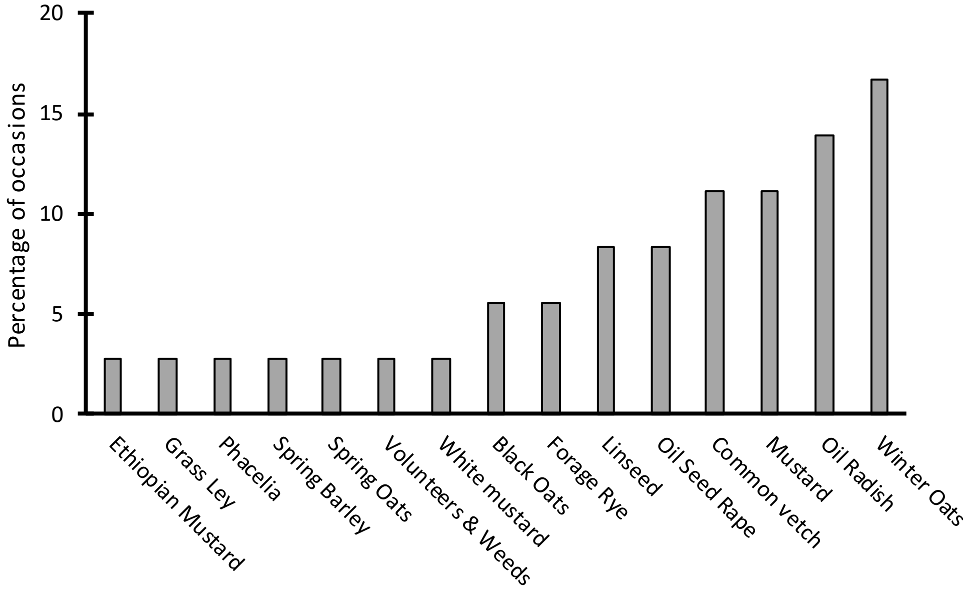
- These results need to be considered carefully as are based on rotation data collected around the UK; therefore, this is not a controlled environment.
- Potato gross margins are significantly higher after cover crops, even if management costs during the cover crop interval are subtracted; this is mainly due to higher yields.
- There are no significant effects on the gross margins for barley, oilseed rape, potatoes and wheat of applying organic amendments during the previous or current interval; indeed, while the unitary costs of nutrients are lower if a larger share comes from organic amendments, and the number of other farm operations decreases, total costs of fertilisation are higher.
- Gross margins per hectare are significantly higher in smaller fields for barley, oilseed rape, potatoes and wheat, and for barley and potatoes this is also due to significantly lower costs.

7. ADDITIONAL ECONOMIC ANALYSIS OF COST OF COVER CROP USAGE

7.1. Surveys of crop and economic performance

Using a simplified survey, platform members were asked their two main reasons for planting cover crop immediately before their potato crops. The most common reason was to improve soil structure (32 %), whilst factors such as increasing soil organic matter (26 %) and soil drying prior to cultivation (21 %) were also identified as important. Grazing and compliance with Environmental Focus Area (EFA) regulation were also identified by some respondents (16 and 5 %, respectively). It is interesting to note that using cover crops to reduce over-winter nitrate leaching was not reported by any respondents. The surveys also indicated a wide range of species used with winter oats and oil radish being the most popular (Figure 24).

Figure 24. Survey results showing cover crop species (used alone or in combination) as reported Grower Platform members.



Data collected from sampling of cover crops in the winter/spring before potatoes were grown allowed for assessment of cover crop biomass, N uptake and C:N ratio (Table 68). The median DM yield for the 199 samples was 3.7 t/ha with an interquartile range of 1.7 to 6.3 t/ha. Similarly, the median N uptake was 70 kg N/ha with an interquartile range of 31 to 115 kg N/ha. Assuming a carbon content of 41 % of dry matter, the median C:N ratio of the cover crops was 20. Carbon to nitrogen ration varied from 16 (lower quartile) to 27 (upper quartile). These relatively, large C:N ratios would suggest that, when incorporated, the cover crop residues are unlikely to release much plant-available N to the subsequent potato crop. An initial analysis has not demonstrated any discernible relationship between cover crop biomass production or N uptake and cover crop species or cost (see later) of establishment and management. Earlier work (Allison *et al*. 1998), demonstrated that cover crop yield was more related to temperature and available water than species or soil mineral N.

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Table 68. Summary of cover crop DM yield, nitrogen uptake and estimated C : N ratio of cover crops used by the Grower Platform (2016-2019, n=199)

	Total cover crop yield (t DM/ha)	Total cover crop nitrogen uptake (kg N/ha)	Estimate* of cover crop C:N ratio
Minimum value	0.3	6	9
Lower (25 %) quartile	1.7	31	16
Median (50 %)	3.7	70	20
Mean and S.E.	3.5 ± 0.25	83 ± 4.7	24 ± 0.9
Upper (75 %) quartile	6.3	115	27
Maximum value	16.2	352	85

* Calculated using measured N concentration, but assuming that C concentration is 41 % of dry matter

In the simplified survey, Grower Platform members were also asked about the cost of cover crop seed and the extra operations associated with planting, managing and defoliating a cover crop. These operations were assumed to be in excess of those used to manage the stubble/residues from the proceeding crop. The cost of these operations were values from standard, industry sources (e.g., Redman, 2019; ABC 2019; NAAC 2019). Using industry standard figures, rather than the grower's own values, probably results in over-estimates of costs (of *c.* 10-15 %) but will allow for a more accurate estimate of the range in cover crop costs which are shown in Table 69. In some cases, seed costs per hectare were very low and these were generally cover crops that either used volunteer cereal and weeds or farm-saved grain. The more expensive cover seed tended to be specialist mixes for EFA compliance or for winter-hardiness in northern regions. Cover crop management costs averaged £225/ha but showed a large variation. The cheaper options tended to involve broadcasting seed and light cultivations to establish the crop and a single herbicide application to destroy the cover crop in the spring. However, cost of destruction will very much depend on how well the cover crop has grown and therefore on weather conditions in autumn/winter. At its simplest, assuming an average benefit of *c*. 3 t/ha from using a cover crop (see report for WP3), a potato value of £150/t and a total cost of establishing, managing and destroying a cover crop of £225/ha, then use of cover crops could be justified solely from an economic standpoint. However, this analysis ignores potential problems that may be associated with integration of cover crop into potato rotation (e.g., problems with slugs and wireworms, or providing hosts for pathogenic, free-living nematodes). Likewise, it also ignores potential benefit that may accrue including reduced fuel consumption for cultivations and benefit elsewhere in the rotation.

Table 69. Summary of cost of cover seed and estimate of total cost of managing a cover crop

	Cost of cover crop seed (£/ha)	Total cost of cover crop (including seed) (£/ha)
Minimum value	0	71
Lower (25 %) quartile	33	176
Median (50 %)	47	209
Mean and S.E.	46 ± 7.1	225 ± 19.0
Upper (75 %) quartile	55	256
Maximum value	140	389

8. REFERENCES

ABC The Agricultural Budgeting and Costing Book (2019). Agro Business Consultants Ltd, Melton Mowbray, Leicestershire.

ALLISON, M.F., ARMSTRONG, M.J., JAGGARD, K.W. & TODD A.D. (1998). Integration of nitrate cover crops into sugar beet (Beta vulgaris) rotations. 1. Management and effectiveness of nitrate cover crops. *Journal of Agricultural Science, Cambridge* **130**, 53-60.

BALL, B, GUIMARÃES, R., BATEY, T, & MUNKHOLM, L. (2012). Visual Evaluation of Soil Structure. https://www.sruc.ac.uk/downloads/file/1121/visual_evaluation_of_soil_structure_score_chart

DRAYCOTT, A.P., DURRANT, M.J. AND WEBB, D.J. (1972). Long-term effects of fertilisers at Broom's Barn. *Rothamsted Report for 1971, Part 2*, pp 155-164.

DRAYCOTT, A.P., DURRANT, M.J. AND WEBB, D.J. (1978). Long-term effects of fertilisers at Broom's Barn. *Rothamsted Report for 1977, Part 2*, pp 15-30.

HOLLAND J, BROWN, J L, MACKENZIE, K, NEILSON, R, PIRAS, S, & MCKENZIE, B M. (2021) Over winter cover crops provide yield benefits for spring barley and maintain soil health in northern Europe. *European Journal of Agronomy* (submitted).

NATIONAL ASSOCIATION OF AGRICULTURAL CONTRACTORS (2019). Contracting Charges Guide 19-20. https://fwi-wp-assets-live.s3-eu-west-1.amazonaws.com/sites/1/2019/06/contractor-charges-2019-20.pdf

REDMAN, G. (2019). The John Nix Pocketbook for Farm Management: 50th Edition.

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