Final Report

Management of Rotations, Soil Structure and Water (Rotations Research Partnership)

Work Package 3 (WP3): Rotations & Resilience

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2. Reporting of Work Package 3

The AHDB Project *Management of Rotations, Soil Structure and Water* (Project 91140001) comprised four interlinked work packages (WPs) designed to achieve the project's objectives. WP 1 included project management and knowledge transfer but also the gathering and analysis of survey data from collaborating growers; the reinstatement of a long-term, rotational experiment at Broom's Barn, Suffolk and conducting some replicated experiments investigating composts and cover crops. The main objective of WP2 was to investigate the use of spatial information (e.g. maps of cereal and potato yields or of soil properties) to define higher and lower yield zones within fields which may then be used to improve crop management practices. In addition, this work package investigates novel scanning technologies to better understand the dynamics of soil organic matter. Much of the experimental work with cover crops and soil amendments were investigated in WP3 and a further output from this work package was decision support tools to aid management of both soil structure and organic matter content. WP4 investigated novel method to quantify root distribution and the effects of soil conditions and crop management on root function and crop productivity.

For simplicity, the key findings of WP3 will be discussed in this report as will background literature, conclusions, appendices. However, practical recommendations from the whole project will be synthesised and reported in the project summary report.

2.1. Areas of work

The work package comprised three primary areas of work:

1. Split-field and some fully replicated and randomised comparisons testing cover crops and amendments on potatoes and other root vegetable (NIAB and Vegetable Consultancy Service (VCS)).
2. Development of a Soil Organic Matter model (Rothamsted Research).
3. Development of the Terranimo model which is used to predict soil damage (compaction) based on axle loadings of farm machinery (James Hutton Institute, Dundee University and Aarhus University)

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

3. SPLIT FIELD COMPARISONS AND LIMITED REPLICATION EXPERIMENTS

Apart from the replicated experiments at Broom's Barn and NIAB described in the report for WP1, numerous experiments were set up in fields belonging to members of the Grower Platform. Many of these experiments were simple, unreplicated 'strip' trials where comparisons were made between the effects of, for example, stubble or a cover crop on the yield of a subsequent potato crop. In some cases, more sophisticated replicated and randomised experiments evaluated the effects of organic amendment or cover crops on the performance of subsequent crops. The majority of experiments used potato as the test crops however some experiments used root vegetable crops, and these were primarily managed by Vegetable Consultancy Services (VCS) as a sub-contract.

3.1. Replicated and unreplicated experiments done by NIAB

3.1.1. Materials and Methods

3.1.1.1. Site selection and management

Conversations with Grower Platform members in the summer/autumn were used to identify possible comparisons of cover crops and amendments for the following season. To avoid overly inconveniencing the host growers, these comparisons were generally simple adaptations to their standard field management. For comparisons involving amendments, amendment was applied to the majority of the field, but no amendment was applied to a strip (typically 24 m wide). In some case, the grower used tarpaulins or similar to keep organic manure off smaller areas of land (typically 10 x 15 m). Similarly, for comparisons involving cover crops, an autumn-sown cover crops were planted in the majority of the fields, but strips (12 to 24 m wide) were left unplanted. At some sites, all the field was planted with a cover crop and then a herbicide was used to kill the cover crops in designated areas. Cover crops were killed shortly after emergence or in late winter/early spring. The location of the strips was recorded using a Trimble Juno T41/5 GPS receiver (accurate to *c*. ± 3 m) or by referencing the strips to fixed reference points in the field margins. Basic agronomic details of the cover crop experiments, and amendments comparisons are shown in Table 1 and Table 2, respectively. These table also include details of trial sites which had to be abandoned.

3.1.1.2. Cover crop sampling

When resources permitted, the cover crops were sampled to assess total dry matter (DM) yield and nitrogen (N) uptake. Ideally, sampling was timed so that maximum standing DM yield was assessed but, in some cases, this was not possible. To sample the crops four or five replicate, quadrat samples (1 m^2) were taken from representative areas of the cover crop. In each quadrat as much cover crop was recovered including tap root and easily recoverable fibrous root. Volunteer cereals and weeds were also included as cover crop. Excess soil and straw were removed, and the sample placed in a labelled potato sack and returned to Cambridge for processing. At Cambridge, any remaining soil was carefully removed by washing and then whole sample was dried to constant weight in a recirculating air, drying oven (95 °C for 48 hours). The dry weight of the cover crop was recorded. The dried samples were sent to NRM Ltd. for determination of total N concentration using a Dumas combustion method.

3.1.1.3. *Sampling and analysis of organic amendment*

For most experiments multiple, representative samples (*c*. 1 kg) of the organic amendment were taken close to the time of application. These sample were either taken from heaps or taken as ‘grab’ samples directly from the spreader during the application process. These samples were chilled and then sent to Natural Resource Management (NRM) Ltd for analysis using standard techniques to determine the composition of the amendment. In another case (e.g. B&C Potatoes), the analysis of the amendment was supplied by the grower.

3.1.1.4. *Potato crop sampling*

The timing of potato crop sampling was determined by conversations with the host grower in relation to their planned desiccation date (if appropriate) and harvest dates. Wherever possible sampling was timed to be after desiccation and as close to harvest date as possible. In each treatment strip between three and five yield samples were taken. Sample areas were selected to be representative of the treatment strip. Within reason, all the samples were clustered to help minimise the effect of field variation (i.e. soil type, topography, seed-stock) on the quantification of treatment effect.

For crops planted as pairs of 0.9144 m (36 “) rows in a 1.8288 m (75 “) bed, the sample area was 3 m of a single row (i.e. 2.74 m^2). For short-season salad crops planted as three rows in a 1.83 m bed, 2 m of bed was sampled (3.66 m^2). The number of plants and mainstems in the harvest area was recorded. The plot was then carefully dug, by hand, and all tubers > 10 mm were removed and place in a labelled potato sack. The tubers were then returned to Cambridge for grading and processing. Tubers were graded into 10 mm increments (by width) and the number and weight of tubers in each size grade was recorded. To calculate tuber dry matter (DM) concentration, a sub-sample (1 kg) of tubers was removed from the grade(s) with the largest yield. This sub-sample was washed, chipped (10 x 10 mm cross section) and weighed. The tuber sub-sample was then dried to constant weight in a recirculating-air, drying oven (95 °C for 48 hr) and the reweighed.

Details of the soil sampling done on the Platform sites is shown after the yield data in Section 3.4.

3.1.1.5. *Statistical Analysis*

For the other unreplicated and non-randomised experiments (the ‘strip-trials’), the mean and standard error are given for each treatment and then the data were analysed collectively using a paired ‘T test.’ Initially, the structure of the T-tests was strictly binary, i.e. the analysis compared control yields with yields following use of an organic amendment with no distinction made for the amendment type or rate of application. However, subsequent analyses grouped organic amendment by type e.g. “low” N (e.g. FYM and compost) or “high N” (e.g. poultry manures).

Table 1. Details of growers, locations and agronomic operations for cover crop experiments in 2016-2020

Experiment	Cover crop species	Cover crop planting date and seed rate (kg/ha)		Cover crop destruction date(s)	Potato variety or species & variety	Date of Planting	Date of Defoliation	Date of sampling
2017-3	Oat and vetch mix	1 Sep 16	25	27 Apr 17	Lady Valora	29 Apr 17	30 Aug 17	18 Sep 17
2017-6	Tillage radish	1 Sep 16	-	22 Apr 17	Piccolo Star	22 Apr 17	Green-top	20 Jul 17
2017-7	Mustard & winter barley	2 Sep 16	6 100	30 Mar 17	Markies	8 Apr 17	14 Sep 17	12 Sep 17
2017-9	Mustard	2 Aug 16	20	5 Oct 16	Orchestra	7 Apr 17	7 Sep 17	21 Sep 17
2017-11	Mustard	7 Sep 16	10	10 Jan 17	Markies	14 Apr 17	23 Sep 17	18 Oct 17
2017-12	Spring oats, linseed and oilseed rape	2 Sep 16	60, 4 and 1.5	31 Mar 17	Fontaine and Maritima	17 Apr 17	12 Sep 17	19 Sep 17
2017-13	Rye, oat and fodder radish mix	n.a.	n.a	8 Mar 17	Electra	n.a.	n.a.	13 Sep 17
2017-15	Oil seed rape and kale mix	n.a.	n.a.		VR808	23 Mar 17	n.a.	6 Sep 17
2017-93	Fumigation Mixes	19 Aug 16	28	25 Nov 16	Onions, Highway	30 Mar 17	11 Oct 17	11 Oct 17
2018-25	Oil radish and rye	30 Sep 17	10 & 10 kg/ha or 15 & 5 kg/ha	3 May 18	Shelford	7 May 18	10 Sep 18	3 Sep 18
2018-28	Volunteer barley	n.a.	n.a.	22 Feb 18	Morene	29 Apr 18	Green-top	24 Sep 18
2018-29	Fodder radish	11 Sep 17	50	7 May 18	Electra	16 May 18	14 Sep 18	18 Oct 18
2018-32	Oats	18 Sep 17	70	9 Mar 18 or 19 Apr 18	Maris Piper	25 Apr 18	n.a.	1 Oct 18
2018-36	Fodder radish, oat, and vetch	18 Aug 17	29-34	20 Mar 18	Innovator and Performa	15 May 18	11 Oct 18	27 Sep 18
2018-42	Crimson clover and black oat ± phacelia; Siletina radish; King's Summer bio-fumigation mix	7 Sep 17	15 or 25; 25; 15	12 Mar 18	Sugar beet[1]	n.a.	n.a.	n.a.
2018-43	Crimson clover and black oat ± phacelia; Siletina radish; King's Summer bio-fumigation mix	7 Sep 17	15 or 25; 25; 15	Abandoned	Onions[1]	n.a.	n.a.	n.a.

Table 1. Details of growers, locations and agronomic operations for cover crop experiments in 2016-2020 (continued)

Experiment	Cover crop species	Cover crop planting date and seed rate (kg/ha)		Cover crop destruction date(s)	Potato variety or species & variety	Date of Planting	Date of Defoliation	Date of sampling
2018-44	Crimson clover and black oat ± phacelia; Siletina radish; King's Summer bio-fumigation mix	7 Sep 17	15 or 25; 25; 15	12 Mar 18	Parsnips	9 May 18	n.a.	12 Dec 18
2018-45	Bio-fumigation mix and cereal	31 Jul 17	12 & 50	13 Sep 17	Cereal	21 Sep 17	n.a.	6 Aug 18
2019-50	Oats	15 Sep 18	75	21 Mar 19 or 1 Apr 19	Maris Piper	5 Apr 19	*	7 Oct 19
2019-51	Grass Ley	1 Apr 16	12	16 Feb 19	Shelford	21 Apr 19	3 Sep 19	25 Sep 19
2019-52	Oil radish, Ethiopian Mustard & White Mustard	29 Sep 18	15	26 Feb 19	Shelford	16 Apr 19	3 Sep 19	25 Sep 19
2019-58	Winter Oats, Linseed & Oil Seed Rape	5 Sep 18	40, 8 & 6	20 Feb 19	Royal	7 Apr 19	12 Sep 19	24 Sep 19
2019-59	Winter Oats, Linseed & Oil Seed Rape	5 Sep 18	40 8 & 6	20 Feb 19	Royal	8 Apr 19	12 Sep 19	24 Sep 19
2019-60	Winter Oats & Common Vetch	25 Aug 18	40 & 20	9 Feb 19	Sagitta	17 Apr 19	28 Sep 19	3 Oct 19
2019-61	Winter Oats & Common Vetch	25 Aug 18	40 & 20	30 Mar 19	Markies	12 Apr 19	19 Sep 19	3 Oct 19
2019-65	Forage Rye, Common Vetch & Oil Radish	*	*	*	*	*	*	*
2019-67	Mustard	15 Aug 18	14	8 Nov 18	Tyson	8 Apr 19	27 Aug 19	21 Aug 19
2019-69	Cover crop	*	*	*	*	*	*	*
2019-71	Oil Radish & Spring Oats	22 Aug 18	10 &16	7 Apr 19	Taurus	23 Apr 19	10 Sep 19	18 Oct 19
2019-72	Forage Rye, Common Vetch & Oil Radish	3 Sep 18	40	19 Mar 19	Gwenne	16 Apr 19	8 Aug 19	22 Aug 19
2020-74	Oats	11 Sep 19	70	18 Mar 20 15 Apr 20 21 Apr 15	Maris Piper	24 Apr 20	n.a.	29 Sep 20
2020-75	Oil Radish	30 Sep 19	18	6 Apr 20	Shelford	*	*	*

Table 1. Details of growers, locations and agronomic operations for cover crop experiments in 2016-2020 (continued)

Experiment	Cover crop species	Cover crop planting date and seed rate (kg/ha)		Cover crop destruction date(s)	Potato variety or species & variety	Date of Planting	Date of Defoliation	Date of sampling
2020-76	Oil Radish	30 Sep 19	18	6 Apr 20	Shelford	8 Apr 20	15 Aug 20	8 Sep 20
2020-77	Vetch, Oil Radish & Oil Seed Rape	25 Aug 19	10, 4 & 4	20 Mar 20	Royal	15 Apr 20	18 Sep 20	9 Sep 20
2020-78	Vetch, Oil Radish & Oil seed Rape	27 Aug 19	10, 4 & 4	20 Mar 20	Royal	13 Apr 20	6 Sep 20	9 Sep 20
2020-79	King's Mustard	6 Aug 19	11	7 Jan 20	Safari	20 Apr 20	9 Sep 20	3 Sep 20
2020-80	Vetch & Rye	27 Sep 19	125	23 Apr 20	Sugar beet, Springbok	23 Apr 20	n.a.	30 Sep 20
2020-82	Winter Oat & Vetch	29 Aug 19	33 & 32	25 Mar 20	Markies	3 Apr 20	21 Sep 20	30 Sep20
2020-83	Winter Oat & Vetch	29 Aug 19	33 & 41	25 Mar 20	Markies	3 Apr 20	21 Sep 20	30 Sep 20
2020-90	Branston Mix & Radish	17 Aug 19	22	6 Jan 20	Gwenne	24 Apr 20	15 Jul 20	30 Jul 20
2020-92	Oat & Oil Radish	30 Aug 19	13	16 Mar 20	Rooster	17 Apr 20	5 Oct 20	14 Oct 20

Table 2. Details of growers, locations and agronomic operations for organic amendment experiments in 2016-2020

Experiment	Type of amendment	Rate (t/ha) and dates of application and incorporation of amendment			Potato variety or species & variety	Date of Planting	Date of Defoliation	Date of sampling
2017-1	Cattle FYM	0 & 59†	7 Oct 16	15 Oct 16	Maris Piper	25 Apr 17	Green-top	4 Oct 17
2017-2	Green waste compost	0 & 30	2 Mar 17	15 Mar 17	Maris Piper	5 Apr 17	Green-top	18 Oct 17
2017-5	Compost	30 30	4 Mar 17	5 Mar 17	Maris Piper	17 Mar 17	Green-top	13 Jul 17
2017-8	Broiler Litter	0, 4 & 8	30 Mar 17	30 Mar 17	Leonardo	8 Apr 17	14 Sep 17	11 Oct 17
2017-10	Duck manure	0 & 130 (experimental rate)	6 Dec 16	7 Dec 16	Maris Peer	5 Jul 17	20 Sep 17	22 Sep 17
2017-14	Green waste compost	0 & 30	12 Dec 16	21 Apr 17	Russet Burbank	21 Apr 17	28 Sep 17	9 Oct 17
2017-15	Cattle FYM	60			VR808	23 Mar 17		6 Sep 17
2017-16	Chicken manure	0 & 8	15 Feb 17	17 Feb 17	Brooke	23 Mar 17	6 Sep 17	6 Sep 17
2017-17	Green waste compost	0, 25 & 50	25 Apr 17	25 Apr 17	Maris Peer	25 Apr 17	7 Aug 17	26 Aug 17
2017-93	Municipal Compost	0, 30	27 Mar 17	29 Mar 17	Onions 'Hyway'	30 Mar 17	11 Oct 17	11 Oct 17
2018-23	Cattle FYM	0 & 59†	7 Oct 16	21 Oct 16	Spring barley 'Laureate'	26 Mar 18	n.a.	21 Aug 18
2018-24	Green waste compost	0, 30 & 60	2 Mar 17	15 Mar 17	Spring wheat 'Chilham'	14 May 18	n.a.	3 Sep 18
2018-26	Pig FYM)	0 & 35	15 Mar 18	16 Mar 18	Lanorma	13 Apr 18	1 Aug 18	24 Jul 18
2018-27	Compost or duck manure	0, 35 & 35	15 Mar 18	16 Mar 18	Marfona	11 Apr 18	11 Jul 18	24 Jul 18
2018-30	Anaerobic digestate	0 & 50	13 May 18	13 May 18	Lanorma	17 May 18	14-Sep-18	10 Oct 18
2018-31	Green waste compost	0 & 30	14 Mar 18	19 Apr 18	Maris Piper	25 Apr 18	n.a.	1 Oct 18
2018-33	Mushroom compost or poultry manure	30 & 8	6 Dec 17 or 8 Feb 18	7 Dec 17 or 8 Feb 18	Brooke	30 Mar 18	5 Sep 18	27 Sep 18

Table 2. Details of growers, locations and agronomic operations for organic amendment experiments in 2016-2020 (continued)

Experiment	Type of amendment	Rate (t/ha) and dates of application and incorporation of amendment			Potato variety or species & variety	Date of Planting	Date of Defoliation	Date of sampling
2018-34	Mushroom compost or poultry manure	0, 30 & 8	15 Dec 17 or 8 Feb 18	9 Feb 18	Performer	21 Apr 18	5 Sep 19	21 Sep 18
2018-35	Pig FYM	0 & 50	15 Feb 18	20 Feb 18	Markies	18 Apr 18	20 Sep 18	27 Sep 18
2018-37	Compost	0 & 30	6 Dec 16 and/or 14 Nov 17	12 Dec 16 and/or 8 May 18	Maris Piper	9 May 18	8 Oct 18	15 Oct 18
2018-38	Compost and FYM	0 &43	26 Oct 2016 and/or 23 Oct 17	27 Oct 16 and/or 25 Oct 17	Vales Sovereign	9 May 18	14 Sep 18	3 Sep 18
2018-39	Compost	0 & 43	21 Oct 16 and/or 15 Dec 17	22 Oct 16 and/or 17 Dec 17	Lanorma	26 Apr 18	29 Jul 18	3 Sep 18
2019-47	Cattle FYM	0 & 59†	7 Oct 16	21 Oct 16	Winter wheat 'Skyfall'	23 Oct 18	*	27 Aug 19
2019-48	Green waste compost	30 & 60	2 Mar 17	27 Mar 17	Winter wheat 'Siskin'	17 Nov 18	*	13 Sep 19
2019-49	Green waste compost	30	1 Apr 19	2 Apr 19	Maris Piper	5 Apr 19	*	3 Oct 19
2019-53	Cattle FYM & Pig FYM	0,40 & 40	22 Feb 19	23 Feb 19	Maris Peer	30 Jun 19	24 Sep 19	16 Sep 19
2019-54	Cattle FYM & Pig FYM	0, 40 & 40	22 Feb 19	23 Feb 19	Bambino	30 Jun 19	24 Sep 19	16 Sep 19
2019-56	Mushroom compost, Pig FYM & Cattle FYM	0,40,40, 40	26 Mar 19	27 Mar 19	Lanorma	19 Mar 19	26 Jul 19	7 Aug 19
2019-57	Mushroom compost, Pig FYM & Cattle FYM	0,40,40, 40	26 Mar 19	27 Mar 19	Maris Piper	*	*	*
2019-62	Mushroom compost, Chicken manure & Pig manure (Jolly FINW)	0, 35, 8, 35	13 Dec 18 & 5 Feb 19	14 Feb 19	Brooke	11 Apr 19	19 Sep 19	9 Oct 19

Table 2. Details of growers, locations and agronomic operations for organic amendment experiments in 2016-2020 (continued)

Experiment	Type of amendment	Rate (t/ha) and dates of application and incorporation of amendment			Potato variety or species & variety	Date of Planting	Date of Defoliation	Date of sampling
2019-63	Chicken Manure & Pig Manure (Jolly F17)	0, 35 & 8	4 Feb 19	11 Feb 19	Shepody	8 Apr 19	*n.a.	12 Aug 19
2019-64	Pig Manure (SML Warners)	25	1 Feb 19	1 Feb 19	Gemson	10 May 19	27 Jul 19	23 Aug 19
2019-68	Pig Manure (SPotN)	36	29 Sep 18	29 Sep 18	Maris Piper	11 Apr 19	10 Sep 19	26 Sep 19
2020-73	Cattle FYM (Brooms Barn)	0 & 59†	7 Oct 16	21 Oct 16	Winter wheat, 'Skyfall'	29 Oct 19	n.a.*	8 Aug 20
2020-80	Greenwaste compost (CS Wretham)	0 & 30	21 Apr 20	23 Apr 20	Sugar beet, 'Springbok'	23 Apr 20	n.a.	30 Sep 20
2020-81	Pig manure (old) (SML Warners)	0 & 25	27 Apr 20	27 Apr 20	Gemson	28 Apr 20	21 Jul 20	23 Jul 20
2020-84	Greenwaste or mushroom compost (Jolly BBreck)	26 & 35	30 Jan 20	31 Jan 20	Onions 'Sturon'	12 Feb 20	23 Jul 20	21 Jul 20
2020-85	Pig manure or poultry manure or mushroom compost (Jolly F18)	0, 35, 9 & 35	11 Mar 20	2020-73	Infinity	13 Apr 20	n.a.	6 Oct 20
2020-87	Cattle FYM (Greenwell RB)	0 & 40	21 Mar 20	21 Mar 20	Lanorma	8 Apr 20	15 Aug 20	25 Aug 20
2020-88	Duck FYM or pig manure full or half rate (Greenwell DW)	0,40, 40 & 20	5 Apr 20	5 Apr 20	Maris Peer	20 Apr 20	12 July 20	27 Jul 20

† Experiment also received historic application of FYM at 61 t/ha every three years from 1965 to 2011.
* Experiment abandoned.
n.a. crop sampled green-top or at complete senescence

3.1.2. Results and Discussion

Results for the Grower Platform experiments that had potato crops grown in 2017 to 2020 are shown in Table 3. For completeness, potato yields from the larger, fully replicated experiments at Broom's Barn and NIAB (see report for WP1) are also included in this table.

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2017-1	12	Control + Control	31.1	91.8	359	67.5	25.5
	12	Control + New FYM	30.4	98.3	407	70.4	24.0
	12	Old FYM + Control	29.6	93.0	415	71.6	22.7
	12	Old FYM + Control	30.7	98.2	431	80.2	22.2
		S.E. (20 D.F.)	0.61 or 0.59*	4.6 or 4.5*	15.6 or 15.8*	2.16 or 1.98*	0.34 or 0.43*
2017-2	10	Control	40.0	113	391	58.8	26.2
	10	Compost	40.0	113	438	62.6	24.4
	10	Compost	40.0	109	413	65.7	24.1
		S.E. (20 DF)	-	3.4	8.6	1.08	0.48
2017-3	6	Control	34.7 ± 0.83	163 ± 6.9	559 ± 20.0	55.7 ± 1.46	22.7 ± 0.37
	6	Cover crop	32.8 ± 1.64	138 ± 11.0	547 ± 37.8	56.4 ± 2.04	21.9 ± 0.86
2017-5	6	Control	27.4	142	422	55.9	21.6
	6	Compost	24.9	129	391	55.1	21.0
	6	Duck Manure	24.9	133	431	55.7	21.8
		S.E. (10 D.F.)	0.80	8.3	24.0	1.48	0.46

* S.E. for comparing same level of Old FYM

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2017-6	3	Grazed	58.3 ± 2.11	192 ± 9.9	1039 ± 63.2	36.3 ± 0.72	18.3 ± 0.146
		Topped	57.1 ± 2.43	199 ± 30.1	933 ± 56.5	35.9 ± 0.85	18.0 ± 0.31
2017-7	4	Winter Barley	43.7 ± 1.49	112 ± 5.2	555 ± 18.7	66.8 ± 5.82	24.6 ± 0.67
		Mustard	43.7 ± 2.57	127 ± 7.35	565 ±39.7	49.4 ±4.8	24.9 ± 0.37
2017-8	4	Control	34.6 ± 1.83	164 ± 13.9	527 ± 27.3	66.5 ± 3.08	21.3 ± 0.41
		FYM-Half rate	32.8 ± 1.49	158 ± 12.2	535 ± 33.5	72.5 ± 6.73	21.0 ± 0.78
		FYM-Full rate	34.7 ± 1.07	164 ± 7.9	473 ± 37.7	63.9 ± 5.47	21.3 ± 1.03
2017-9	4	Control	28.3 ± 2.73	104 ± 17.1	588 ± 47.23	71.6 ± 1.495	17.2 ± 0.05
		Mustard	28.3 ± 1.75	105 ± 4.58	590 ± 38.3	69.8 ± 4.25	17.4 ± 0.18
2017-10	4	Control	64.3 ± 2.85	259 ± 29.7	1032 ± 62.1	28.5 ± 1.24	19.2 ± 0.36
		Poultry Manure	62.2 ± 6.26	284 ± 28.6	1037 ± 49.7	29.9 ± 1.06	17.3 ± 0.31

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2017-11	6	Control	27.3	173	616	67.0	22.0
		Cover Crop	27.3	173	625	68.6	20.4
		S.E. (5 D.F.)	1.63	11.8	28.6	1.15	0.53
2017-12	4	Control	25.5 ± 0.0	92 ± 8.4	340 ± 26.0	44.3 ± 0.66	20.8 ± 0.89
		Radish	24.6 ± 0.90	106 ± 11.2	334 ± 30.8	41.6 ± 4.36	20.8 ± 0.26
		Winter Barley	20.0 ± 1.07	89 ± 3.2	272 ± 24.0	35.5 ± 1.62	20.1 ± 0.61
2017-13	4	Grazed+Sprayed	31.9 ± 1.75	215 ± 16.5	328 ± 16.0	57.5 ± 2.56	16.4 ± 0.29
		Un-grazed	32.8 ± 1.49	205 ± 26.1	328 ± 14.7	59.5 ± 5.52	16.7 ± 0.18
2017-14	6	Control	32.2	120	427	72.0	24.1
		Compost	34.6	125	472	77.7	23.4
		S.E. (10 D.F.)	1.52	6.5	24.2	1.51	0.41
2017-15	4	Cover Crop	44.7 ± 3.78	162 ± 10.6	545 ± 22.6	46.1 ± 0.63	26.6 ± 0.48
		FYM	52.0 ± 1.75	181 ± 14.7	630 ± 32.1	43.5 ± 2.19	26.7 ± 0.50

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2017-16	4	Control	39.2 ± 0.90	53.0 ± 4.3	350 ± 56.6	31.9 ± 1.96	27.9 ± 0.37
		Poultry Manure	35.5 ± 1.75	52.0 ± 5.02	377 ± 19.1	52.7 ± 1.97	26.6 ± 0.29
2018-25	4	Control	36.5 ± 2.57	303 ± 22.9	653 ± 30.7	46.3 ± 4.71	22.7 ± 0.44
	4	50OR+50Rye	32.8 ± 1.49	271 ± 12.1	587 ± 29.6	57.2 ± 1.66	21.9 ± 0.37
	4	75OR+25Rye	40.1 ± 1.47	300 ± 6.6	677 58.0	57.3 ± 1.42	22.2 ±0.50
2018-26	4	Control	30.1 ± 0.90	131 ± 11.5	445 ± 7.3	49.2 ± 3.02	19.7 ± 0.37
	4	Pig FYM	30.1 ± 1.75	119 ± 11.7	411 ± 12.9	42.5 ± 3.66	19.9 ± 0.26
2018-27	12	Control	39.8	148	478	35.2	18.6
	12	Compost	39.3	148	457	32.0	18.1
	4	Pig-FYM	39.2	139	442	32.3	18.2
		S.E. (22 D.F.)	0.75 or 1.30	7.5 or 13.1	18.6 or 32.3	0.89 or 1.54	0.18 or 0.32

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2018-28	4	Control	31.0 ± 1.04	80 ± 1.47	434 ± 16.8	52.8 ± 6.29	22.4 ± 0.52
	4	Cover crop	29.2 ± 0.00	95 ± 6.7	502 ± 22.4	62.6 ± 3.01	22.8 ± 0.23
2018-29	3	Control	26.2 ± 0.00	115 ± 7.3	287 ± 14.8	58.9 ± 1.94	15.8 ± 0.27
	3	Ungrazed	26.2 ± 0.00	130 ± 7.3	297 ± 24.1	65.7 ± 5.37	15.7 ± 0.15
	3	Grazed	26.2 ± 0.00	120 ± 5.26	370 ± 16.2	79.6 ± 0.58	16.6 ± 0.03
2018-30	3	Control	21.9 ± 0.00	107 ± 1.23	345 ± 8.0	53.1 ± 1.82	17.8 ± 0.20
	3	Digestate	21.9 ± 0.00	105 ± 3.23	322 ± 4.9	62.4 ± 2.37	17.7 ± 0.36
2018-31	16	Control	44.4	116	602	44.9	25.5
	16	Compost	44.4	109	576	48.7	25.7
		S.E. (20 D.F.)	-	3.5	14.6	1.21	0.30
2018-32	8	Control	44.4	113	609	55.7	26.2
	8	Defoliated	44.4	116	582	50.4	26.7
	8	Undefoliated	44.4	112	600	55.9	26.1
		S.E. (14 D.F.)	-	3.1	13.5	1.53	0.27

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2018-33	4	Compost	34.6 ± 1.83	148 ± 18.7	606 ± 32.7	66.8 ± 3.16	25.2 ± 0.26
	4	Poultry manure	32.8 ± 2.57	156 ± 9.1	566 ± 40.1	70.4 ± 4.21	23.8 ± 0.14
2018-34	4	Control	32.8 ± 2.98	102 ± 7.16	280 ± 21.8	71.2 ± 2.82	22.1 ± 0.25
	4	Compost	32.9 ± 2.11	111 ± 12.3	292 ± 22.3	58.2 ± 2.31	21.0 ± 0.44
	4	Poultry manure	33.8 ± 1.75	129 ± 12.1	360 ± 26.2	62.6 ± 3.78	22.0 ± 0.22
2018-35	4	Control	40.1 ± 1.47	94 ± 10.7	453 ± 33.0	45.7 ± 4.46	24.3 ± 0.24
	4	Pig FYM	41.9 ± 1.04	88 ± 4.0	397 ± 19.0	56.0 ± 2.26	23.8 ± 0.65
2018-36	4	Fodder radish + oat	33.7 ± 3.43	163 ± 18.1	372 ± 27.7	61.4 ± 5.05	21.9 ± 0.31
	4	Fodder radish + vetch	33.8 ± 1.75	178 ± 18.6	365 ± 12.0	59.1 ± 3.47	20.6 ± 0.71
	4	Fodder radish + oat	41.0 ± 2.29	165 ± 21.9	360 ± 22.2	56.1 ± 1.43	21.0 ± 0.31

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2018-37	4	Control	31.0	117	602	75.0	21.0
	4	2016	29.2	109	574	70.5	19.6
	4	2016-17	31.9	123	591	79.3	19.9
	4	2016-17-18	31.0	114	560	74.4	20.6
		S.E. (12 D.F.)	1.36	8.6	21.1	2.84	0.34
2018-38	3	Compost-2017	42.5 ± 0.93	212 ±9.5	748 ± 26.2	79.5 ± 1.93	18.0 ± 0.26
	3	Muck-2016 + Compost 2017	41.9 ± 1.82	210 ± 13.0	736 ± 46.5	78.9 ± 3.70	18.1 ± 0.34
2018-39	5	Control	32.1 ± 1.79	108 ± 14.5	437 ± 47.0	71.4 ± 4.15	17.1 ± 0.42
	5	Compost in 2017	32.8 ± 1.15	113 ± 14.5	459 ± 27.8	69.6 ± 2.44	17.4 ± 0.31
	5	Compost in 2016 and 2017	32.1 ± 0.72	120 ± 5.53	424 ± 10.9	64.8 ± 3.97	16.8 ± 0.75
2019-49	16	Control	44.4	124	495	55.5	23.7
	16	Compost	44.4	115	469	56.9	23.1

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2019-50	8	Control	44.4	126	467	66.1	22.8
	8	Defoliated	44.4	119	459	66.1	23.0
	8	Undefoliated	44.4	113	455	69.6	22.3
		S.E. (14 D.F.)	-	6.0	22.0	1.80	0.37
2019-51	4	Control	34.7 ± 1.07	156 ± 5.8	395 ± 16.9	50.1 ± 5.40	25.1 ± 0.72
	4	Grass Ley	37.4 ± 1.75	178 ± 18.6	434 ± 9.1	50.3 ± 2.42	25.5 ± 0.40
2019-52	4	Control	32.8 ± 1.49	164 ± 10.0	523 ± 16.9	50.0 ± 4.35	23.2 ± 0.47
	4	Cover crop	34.7 ± 1.07	180 ± 11.8	533 ± 36.7	49.8 ± 1.05	24.3 ± 1.25
2019-53	2	Control	92.5 ± 5.45	474 ± 7.3	1088 ± 12.8	37.8 ± 0.39	18.7 ± 0.50
	2	Cattle manure	103.9 ± 5.50	445 ± 7.3	1086 ± 29.2	33.0 ± 1.62	18.6 ± 0.57
	2	Pig manure	105.7 ± 0.00	465 ± 31.0	1136 ± 42.0	35.3 ± 1.65	19.3 ± 0.35

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2019-54	2	Control	91.1 ± 0.00	478 ± 0.0	1086 ± 36.5	42.3 ± 0.03	17.6 ± 0.11
	2	Cattle manure	89.3 ± 9.10	488 ± 11.0	1259 ± 34.7	41.6 ± 0.96	± 17.6 ± 0.28
	2	Pig manure	102.1 ± 3.65	474 ± 3.6	1427 ± 31.0	44.7 ± 3.87	17.8 ± 0.86
2019-56	3	Control	33.7 ± 0.93	87 12.9	446 ± 61.8	70.1 ± 6.34	18.2 ± 0.19
	3	Mushroom compost	38.3 ± 1.04	89 ± 7.66	363 ± 26.4	64.1 ± 2.83	18.1 ± 0.32
	3	Duck manure	35.6 ± 0.93	98 ± 5.8	445 ± 38.0	63.5 ± 4.39	18.1 ± 0.35
	3	Pig manure	34.7 ± 1.07	85 ± 2.73	393 ± 14.2	66.3 ± 2.17	18.2 0± .27
2019-58	4	Control	32.8 ± 0.00	115 3.8	425 ± 33.9	69.0 ± 5.3	24.2 ± 0.35
	4	Cover crop	32.8 ± 1.49	97 ± 6.4	425 ± 31.2	75.8 ± 4.29	23.6 ± 0.42

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2019-59	4	Control	32.8 ± 1.49	103 ± 8.7	357 ± 33.0	60.9 ± 6.66	23.6 ± 0.79
	4	Cover crop	33.8 ± 1.75	107 ± 13.5	363 ± 20.8	71.6 ± 3.18	23.4 ± 0.37
2019-60	4	Control	36.5 ± 0.00	147 ± 4.0	539 ± 15.1	81.4 ± 1.81	20.5 ± 0.19
	4	Cover crop	36.5 ± 1.49	163 ± 4.6	567 ± 29.3	81.2 ± 1.74	20.4 ± 0.96
2019-61	4	Control	31.9 ± 1.75	100 ± 10.6	444 ± 27.7	45.9 ± 1.78	24.0 ± 0.13
	4	Cover crop	33.7 ± 1.75	105 ± 7.4	479 ± 29.4	49.6 ± 2.44	23.8 ± 0.52
2019-62	4	Control	34.7 ± 1.83	55 ± 7.4	359 ± 8.5	43.3 ± 2.30	24.6 ± 0.23
	4	Mushroom compost	36.5 ± 0.00	60 ± 4.8	394 ± 24.0	47.0 ± 1.70	23.4 ± 0.21
	4	Chicken manure	35.6 ± 1.75	65 ± 10.7	348 ± 33.9	46.9 ± 1.92	23.3 ± 0.18
	4	Pig manure	35.6 ± 0.93	55 ± 3.9	379 ± 23.7	43.3 ± 1.20	23.7 ± 0.19

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2019-63	4	Control	31.0 ± 2.36	68 ± 3.81	294 ± 9.2	55.5 ± 2.69	24.0 ± 0.34
	4	Pig manure	32.8 ± 0.00	67 ± 3.1	277 ± 11.0	60.3 ± 2.04	21.5 ± 0.46
	4	Chicken manure	32.8 ± 1.49	78 ± 4.0	321 ± 23.4	58.0 ± 4.03	23.0 ± 0.52
2019-64	4	Control	88.2 ± 4.64	445 ± 66.9	1152 ± 109.0	42.9 ± 1.32	17.9 ± 0.18
	4	Cattle FYM	88.2 ± 3.42	610 ± 100.6	1541 ± 181.6	46.4 ± 1.59	18.2 ± 0.21
2019-67	4	Control	32.8 ± 0.00	75 ± 1.8	633 ± 3.5	59.1 ± 6.81	20.2 ± 0.19
	4	Cover crop	33.7 ± 0.93	75 ± 3.5	623 ± 19.0	61.9 ± 4.04	20.6 ± 0.37
2019-68	3	Control	31.6 ± 1.20	128 ± 9.16	366 ± 31.7	64.6 0.97	20.2 ± 0.16
	3	Pig Manure	31.6 ± 1.20	123 ± 12.3	378 ± 36.8	65.7 ± 1.36	20.0 ± 0.18

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2019-71	3	Control	30.0 ± 3.21	54 ± 5.3	435 ± 22.1	53.8 ± 2.67	22.7 ± 0.53
	3	Cereal	38.9 ± 1.20	73 ± 7.3	436 ± 28.6	57.0 ± 1.53	22.4 ± 0.45
	3	Bio-fumigant	38.9 ± 1.20	77 ± 5.6	534 ± 24.9	59.8 ± 1.30	22.8 ± 0.31
2019-72	4	Control	36.5 ± 2.67	220 ± 6.4	850 ± 24.3	31.9 ± 2.18	18.8 ± 2.35
	4	Cover crop	36.5 ± 2.35	217 ± 3.5	822 ± 24.6	30.2 ± 1.07	19.6 ± 0.49
2020-74	24	Mean	44.4	115	541	61.6	22.8
	8	Early defoliated	44.4	132	612	66.7	22.5
	8	Late defoliated	44.4	106	513	58.8	23.0
	8	Undefoliated	44.4	107	497	59.4	22.9
		S.E. (14 D.F.)	-	4.8	19.8	1.26	0.25
2020-76	4	Control	38.3 ± 2.34	161 ± 6.9	296 ± 13.1	56.6 ± 2.40	23.3 ± 1.07
	4	Oil radish	34.7 ± 1.07	191 ± 4.8	338 ± 9.0	63.9 ± 3.10	22.5 ± 0.62
2020-77	4	Cover crop	33.8 ± 2.73	147 ± 6.2	323 ± 13.7	63.9 ± 1.83	20.2 ± 0.49

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%)
2020-78	4	Cover crop	34.7 ± 1.07	129 ± 10.6	353 ± 45.3	66.3 ± 4.62	22.5 ± 0.33
2020-79	4	Control	33.7 ± 0.93	60 ± 4.8	271 ± 14.8	58.8 ± 3.41	18.0 ± 0.27
	4	Mustard	35.6 ± 0.93	69 ± 2.11	325 ± 5.2	64.6 ± 2.03	17.8 ± 0.15
2020-81	4	Control	72.5 ± 4.26	412 ± 24.1	1333 ± 58.1	34.1 ± 2.42	16.4 ± 0.15
	4	Pig manure	98.4 ± 3.87	385 ± 7.3	1584 ± 50.5	41.6 ± 0.84	17.1 ± 0.26
2020-82	4	Control	29.2 ± 1.49	92 ± 13.8	316 ± 26.3	51.3 ± 8.06	20.9 ± 0.84
	4	Oat & vetch	29.2 ± 1.49	84 ± 4.9	300 ± 17.0	54.3 ± 2.08	20.1 ± 0.79
2020-83	4	Control	31.9 ± 1.75	95 ± 6.7	382 ± 29.5	56.0 ± 6.37	16.9 ± 1.01
	4	Oat & vetch	31.0 ± 1.04	85 ± 7.9	341 ± 15.4	68.3 ± 4.00	17.0 ± 0.48

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%/ha)
2020-85	4	Control	48.3 ± 0.90	194 ± 16.6	476 ± 48.4	50.1 ± 2.14	26.1 ± 0.22
	4	Pig manure	50.1 ± 4.79	225 ± 18.2	513 ± 14.6	53.4 ± 3.86	25.0 ± 0.53
	4	Mushroom compost	50.1 ± 2.73	200 ± 13.9	487 ± 28.1	52.9 ± 2.43	25.3 ± 0.57
	4	Poultry manure	52.0 ± 3.46	198 ± 10.8	464 ± 18.5	57.6 ± 1.36	24.0 ± 0.56
2020-87	4	Control	33.8 ± 1.75	126 ± 5.7	522 ± 33.5	89.8 ± 3.46	17.2 ± 0.32
	4	Cattle FYM	36.5 ± 1.49	134 ± 6.0	509 ± 16.9	85.6 ± 5.63	19.1 ± 0.74
2020-88	4	Control	100 ± 4.7	494 ± 42.7	1658 ± 106.0	51.5 ± 0.46	16.4 ± 0.26
	4	Pig manure-half	98.4 ± 4.47	488 ± 40.9	1597 ± 179.0	54.0 ± 1.32	15.9 ± 0.38
	4	Pig manure-full	95.7 ± 1.56	498 ± 14.6	1511 ± 137.3	56.6 ± 4.92	15.5 ± 0.39
	4	Duck manure	103 ± 3.4	484 ± 33.2	1537 ± 137.5	52.4 ± 1.60	16.2 ± 0.35

Table 3. Main effects of cover crops or organic amendments on components of potato yield in 2017-2020 (continued)

Experiment	Number of replicates in treatment mean	Treatment	Plant population (000/ha)	Stem population (000/ha)	Total tuber population (000/ha)	Total tuber FW yield (t/ha)	Tuber DM concentration (%/ha)
2020-90	4	Radish-control	80.2 ± 2.57	498 ± 44.3	1072 ± 45.4	34.1 ± 1.07	15.5 ± 0.30
	4	Radish-chopped	83.8 ± 2.57	531 ± 13.3	1129 ± 43.9	39.1 ± 1.00	15.8 ± 0.44
	4	Radish-compacted	77.5 ± 2.73	502 ± 25.1	1160 ± 14.6	36.8 ± 0.27	15.0 ± 0.24
2020-92	4	Control	26.4 ± 0.93	134 ± 11.4	492 ± 22.8	73.4 ± 2.98	21.0 ± 0.13
	4	Oat & oil radish	26.4 ± 0.93	117 ± 5.4	453 ± 37.1	68.9 ± 2.93	21.5 ± 0.83

3.2. Summary of 2016-20 work with amendments and cover crops

The results from the replicated experiments and unreplicated ‘strip’ trials have been documented earlier in this report. To combine these data into useful summaries the following approaches were used. Experiments were first coded by crop type (0 = abandoned trial, 1 = potato, 2 = field vegetable crop and 3 = cereal). Codes (0 or 1) were also created for invalid or valid cover crop or organic amendment comparisons. A comparison was valid if there was a suitable control. For organic amendment comparisons a suitable control was one where no organic material had been applied. For the cover crop data, a valid control was one where a cover crop had never been planted or had been planted but sprayed-off at emergence. In addition, cover crop comparisons were also considered to be valid if the cover crop in the control area was removed at least 6 weeks before the treated area. For this analysis, all cover crops were equivalent irrespective of species composition. However, for the amendment comparisons, the analysis was extended to enable differentiation between poultry manures which have a relatively large concentration of readily available nutrients and other amendments. For the statistical analysis, each paired comparison was given equal weighting irrespective of whether data were derived from fully randomised and replicated experiments or simple strip trials. Similarly, the data were given equal weighting irrespective of the number of replicates that comprised the mean yield.

Summaries of the combined effect of organic amendments and cover crops on total FW potato are shown in Figure 1 and Figure 2, respectively. In total there were 32 valid comparisons. Of these, use of cover crop reduced yield by > 1 t/ha in 7 instances (22 %) and increased tuber yield by >1 t/ha in 19 instances (59 %). The mean control yield was 56.6 t/ha compared with 59.6 t/ha when a cover crop was grown. Numerically, cover crops were associated with a small increase in the yield of cereals but a small decrease in the yield of root vegetables, but these differences were too small to be of statistical significance. The effects of organic amendments were assessed on 38 crops. Of these, use of organic amendments was associated with yield decrease of > 1 t/ha in 12 instance (32 % of crops) and was associated with a yield increase of > 1 t/ha in 20 crops (53 %). For the amendment comparison, the mean control yield was 55.2 t/ha and 56.5 t/ha when an amendment was use. Statistical analyses of these data are shown in Table 4. For potato crops, use of a cover crops was associate with an increase in yield of c. 3.0 t/ha and this increase in yield was statistically significant (P=0.013). Use of organic amendment was associated with a smaller increase in tuber yield (1.3 t/ha), but this difference was too small to be statistically significant (P=0.125).

Figure 1. Summary of effects of organic amendments on total FW yield of potato (t/ha) in 2017-2020. Control yields are the unshaded bars, and the effects of the amendment (positive or negative) are indicated by the shaded bars. The individual experiments have been arranged in order of yield increase. See individual experiments for details.

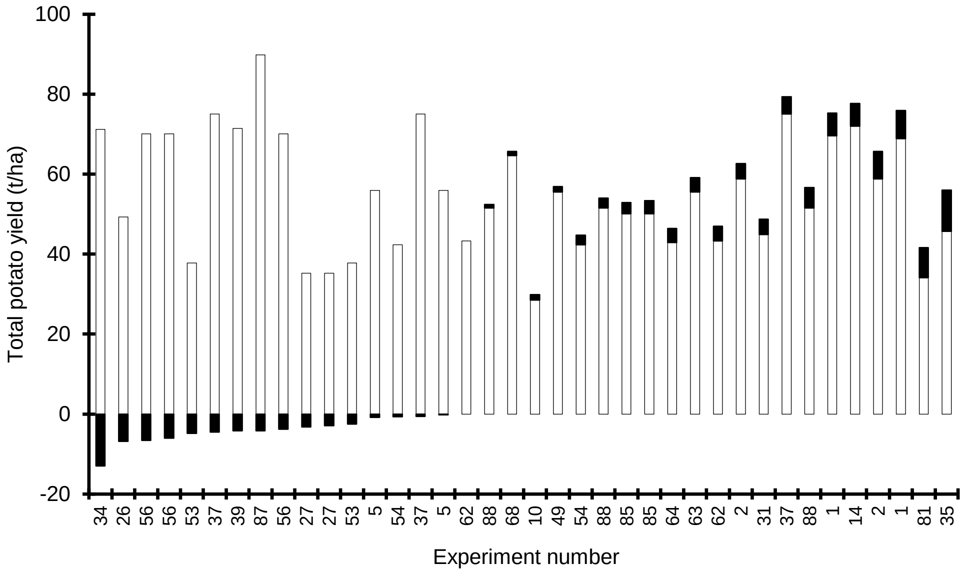


Figure 2. Summary of effects of cover crops on total FW yield of potato (t/ha) in 2017-2020. Control yields are the unshaded bars, and the effects of the cover crop (positive or negative) are indicated by the shaded bars. The individual experiments have been arranged in order of yield increase. See individual experiments for details.

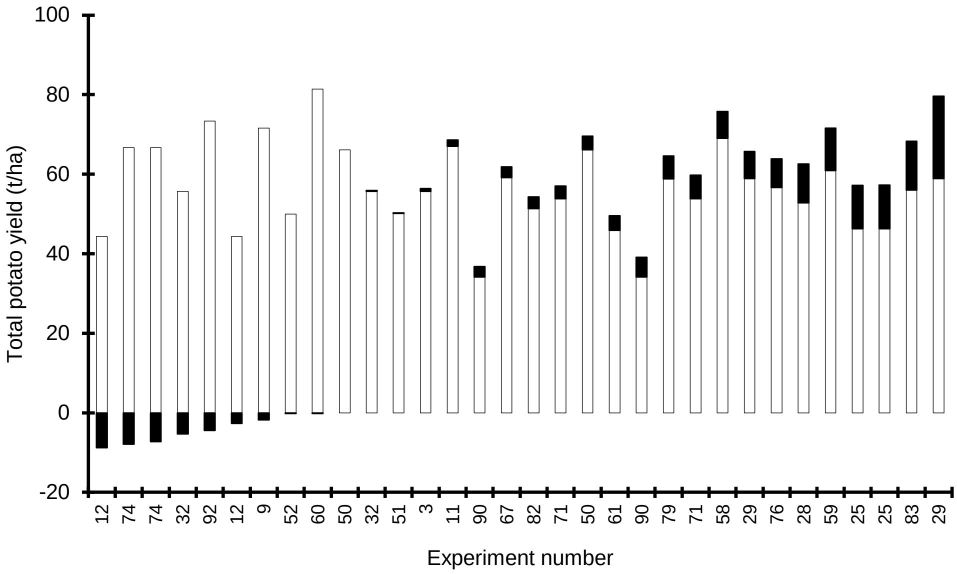


Table 4. Summary of effect of cover crops or organic amendments on yield of all crops, potatoes and root vegetables and cereals (see text for methodology)

	Effect of cover crops on yield of		
	All crops	Potatoes	Root vegetable or cereals
Number of paired comparisons	52	32	20
Control yield (t/ha, and S.E.)	53.9 ± 2.24	56.6 ± 1.90	49.5 ± 4.88
Treatment yield (t/ha, and S.E.)	54.9 ± 2.32	59.6 ± 2.04	47.4 ± 4.67
Difference in yields (t/ha and S.E.)	1.1 ± 0.93	3.0 ± 1.14	-2.1 ± 1.54
T statistic on difference is 0	1.09	2.62	-1.34
Probability difference is due to chance	0.283	0.013	0.197

	Effect of all organic amendments on yield of		
	All crops	Potatoes	Root vegetables or cereals
Number of paired comparisons	54	46	8
Control yield (t/ha, and S.E.)	49.6 ± 2.75	55.2 ± 2.11	17.4 ± 6.87
Treatment yield (t/ha, and S.E.)	50.7 ± 2.74	56.5 ± 2.00	17.2 ± 6.93
Difference in yields (t/ha and S.E.)	1.1 ± 0.74	1.3 ± 0.86	-0.3
T statistic on difference is 0	1.50	1.56	-0.44
Probability difference is due to chance	0.140	0.125	0.675

	Effect of non-poultry organic amendments on yield of		
	All crops	Potatoes	Root vegetables or cereals
Number of paired comparisons	50	38	12
Control yield (t/ha, and S.E.)	45.1 ± 3.35	55.3 ± 2.39	12.9 ± 4.87
Treatment yield (t/ha, and S.E.)	45.5 ± 3.37	55.9 ± 2.35	12.8 ± 4.89
Difference in yields (t/ha and S.E.)	0.4 ± 0.61	0.6 ± 0.79	0.1 ± 0.39
T statistic on difference is 0	0.70	0.73	0.19
Probability difference is due to chance	0.489	0.468	0.850

3.3. Replicated and unreplicated experiments by Vegetable Consultancy Services

A component of this work package was to examine the effects of cover crops and organic amendments on individual root vegetable crops (e.g. onions, parsnips) or on intensive root vegetable rotations typical of east Anglia. This work was sub-contacted by NIAB CUF to Vegetable Consultancy Services (VCS) Ltd. In total, VCS were responsible for nine experiments (2017-21, 2017-22, 2017-93, 2018-42, 2018-43, 2018-44, 2018-46, 2019-66 and 2020-80) that assessed the effects of previous cover crops or amendment on the crop yield. Due to poor germination and growth of the cover crops in some experiments these were abandoned, and no yield data were collected from the test crops.

3.3.1. Materials and Methods

Agronomic information relating to the VCS experiments are shown in Table 1 and Table 2. Some supplementary information is given below for individual experiments.

Experiment 2017-93. In autumn 2016, strips of different cover crop species were planted in two fields together with an unplanted strip of fallow ground to act as a control. The fresh weight biomass of the cover crops was assessed in November 2016 and January 2017. In March 2017, the onion variety Red Tide was planted and was sampled late August 2017. At this sampling, onion yields, and bulb populations was measured as was the severity of Fusarium. These assessments were made using standard industry protocols.

Experiments 2018-46, 2019-66 and 2020-80 were a replicated rotational experiment that compared the effects of cover crops or organic amendment on crop yields. The experiment was near Illington, Norfolk (52.4677 °N, 0.8402 °E) on land farmed by RG Abrey. The field was a loamy sand (88 % sand, 8 % silt and 4 % clay) with 1.7 % organic matter. The experiment comprised three blocks of nine plots. In each block, three treatments (control, autumn sown cover crop or spring applied amendment) were allocated at random to each of three plots. Each plot was 6 m wide and 6 m long. The experiment started in 2018 with a crop of maize that was planted without prior cover crop or amendment. The maize crop was used to help remove residual effects from previous cropping practices and to provide a convenient entry point for establishment of the first cover crop in Autumn 2018. In 2019 and 2020, the plots were planted with spring barley and sugar beet, respectively. In 2021, the cover crop and amendment treatments were repeated but three different test crops used: onions, potatoes and carrots. Some key agronomic details of the experiment are shown in Table 5.

Table 5. Details of agronomic operations at the VCS experiment at Illington, Norfolk

Cropping year	2018	2019	2020
Experiment code	2018-46	2019-66	2020-80
Cover crop species	-	Bento oil radish	Vetch & rye
Cover crop seed rate (kg/ha)	-	20	125
Cover crop planting date	-	25 Sep 18	27 Sep 19
Cover crop destruction date	-	1 Apr 19	23 Apr 20
Compost application rate (t/ha)	-	30	30
Compost application date	-	19 Mar 19	21 Apr 20
Test crop	Maize	Spring barley (*cv* Propino)	Sugar beet (*cv* Skyfall)
Planting date	25 Apr 18	1 Apr 19	23 Apr 20
Sampling date	17 Aug 18	27 Aug 19	30 Sep 20

3.3.2. Results and Discussion

3.3.2.1. Unreplicated strip trials

The effects of different cover species on onion bulb population, yield and fusarium severity are shown in Table 6 and Table 7. The experiment at Herringswell in 2017 (Table 8) compared organic amendment and cover crops. This experiment was affected by fusarium and the average gross, harvested yield was modest. Neither use of compost or cover crop had any statistically significant effect on total or marketable yield although there were some numeric benefits from use of a cover crop. Table 9 shows the effect of previous cover crops on parsnip population, total and marketable yield. The effects of different cover species on the biomass of cover crops and its effect on subsequent onion crops are shown in Table 10 and Table 11. Collectively, there was some evidence that the black oat, phacelia and crimson clover cover crop was associated with smaller bulb yields and populations.

Table 6. Effect of cover crop species on yield and quality of onions (VCS, Expt 2017-21)

	Number of bulbs (000/ha)	Total bulb FW yield (t/ha)	Total fusarium (% of total yield)
Control	526 ± 14.0	68.2 ± 1.90	15.4 ± 1.58
Bio-fumigation summer-mix	471 ± 16.2	56.6 ± 1.33	12.4 ± 3.69
Bio-fumigation radish	516 ± 7.2	63.3 ± 1.57	12.1 ± 2.70
Crimson cover + forage rye	484 ± 12.1	61.7 ± 2.32	13.0 ± 1.50
Black oat + phacelia + crimson clover	380 ± 42.5	53.6 ± 4.24	14.1 ± 1.37
Forage rye + vetch	495 ± 16.9	64.0 ± 2.68	7.9 ± 1.31

Table 7. Effect of cover crop species on yield and quality of onions (VCS, Expt 2017-22)

	Number of bulbs (000/ha)	Total bulb FW yield (t/ha)	Total fusarium (% of total yield)
Control	504 ± 16.0	66.3 ± 1.68	6.4 ± 2.48
Bio-fumigation summer-mix	596 ± 5.0	76.3 ± 2.23	9.1 ± 3.10
Bio-fumigation radish	510 ± 16.5	67.2 ± 2.58	13.2 ± 2.01
Crimson cover + forage rye	499 ± 13.5	69.7 ± 1.59	11.4 ± 3.05
Black oat + phacelia + crimson clover	306 ± 7.73	48.6 ± 4.39	7.8 ± 2.17
Forage rye + vetch	497 ± 12.8	66.7 ± 0.56	8.9 ± 1.79

Table 8. Experiment 2017-93. Effect of previous cover crop or amendment on population and yield of onion. VCS Ltd, Herringswell

	Population (000/ha)	Harvested FW yield (t/ha)	Cured FW yield (t/ha)	Marketable FW yield (t/ha)
Control	331	36.3	29.7	15.8
Municipal compost	323	32.7	31.6	15.7
Fumigation Mix 1	358	41.4	34.1	17.9
Fumigation Mix 2	325	36.6	30.5	16.0
Fumigation Mix 3	371	37.2	31.7	20.3
Mean	342	36.8	31.5	17.1
S.E. (12 D.F.)	34.7	2.04	3.58	2.63

Table 9. Effect of cover crop species on yield and quality of parsnips (VCS, Expt 2018-44)

	Number of roots (000/ha)	Total FW yield (t/ha)	Total fanged roots (% of total yield)
Control	268 ± 7.5	35.6 ± 0.68	0.8 ± 0.47
Crimson clover + black oat	285 ± 7.4	37.2 ± 1.42	3.9 ± 1.44
Black oat, phacelia, crimson clover	243 ± 4.3	33.7 ± 1.28	0.3 ± 0.30
Siletina radish	239 ± 21.0	28.2 ± 1.24	2.4 ± 1.92
Bio fumigation Summer Mix	294 ± 11.1	36.7 ± 1.43	1.1 ± 0.66

Table 10. Effect of cover crop species on cover crop biomass, yield and quality of onions in Expt. 2017-24

	Cover crop yield (t FW/ha)		Onion		Total fusarium* (percent of yield)
	4 Nov 16	5 Jan 17	population(000/ha)	yield (t/ha)	
Bio-fumigant summer mix	28.5	27.9	474	56.7	12.3
Bio-fumigant radish	25.8	21.6	527	63.6	12.1
Crimson clover & forage rye	13.0	49.7	488	61.8	12.9
Black oat, phacelia & crimson clover	18.2	-	384	53.7	14.1
Forage rye & vetch	21.4	-	499	64.1	7.9
Fallow (control)	-	-	534	68.4	15.4

* Total fusarium is the sum of black spot, corky base, rot and field fusarium

Table 11. Effect of cover crop species on cover crop biomass, yield and quality of onions in Expt. 2017-25

	Cover crop yield (t FW/ha)		Onion		Total fusarium* (percent of yield)
	4 Nov 16	5 Jan 17	population(000/ha)	yield (t/ha)	
Bio-fumigant summer mix	42.6	34.5	601	76.4	9.1
Bio-fumigant radish	44.0	25.1	516	67.3	13.2
Crimson clover & forage rye	16.8	24.6	507	70.0	11.4
Black oat, phacelia & crimson clover	31.5		309	48.7	7.8
Forage rye & vetch	24.2		501	65.9	8.9
Fallow (control)			511	66.5	6.4

* Total fusarium is the sum of black spot, corky base, rot and field fusarium

3.3.2.2. *Replicated rotational experiment at Illington, Norfolk*

The average yield of the maize crop (grown without prior cover crops or amendments) was 40 t FW/ha and indicated a yield gradient from Block 1 to Block 3 (data not shown). The effect of the cover crop and organic amendment on the yields of a spring barley crop grown in 2019 are shown in Table 12. Overall, the yields of the spring barley crop were poor, and this is likely to be a consequence of drought stress brought about by periods of high evaporative demand and exacerbated by a soil with very limited water holding capacity. Numerically, when compared with the untreated control, grain yields were larger when a previous cover crop or organic amendment had been used. However, these differences were small and not statistically significant. The sugar beet crop compared the effects of cover crops and amendments used in the two previous seasons against an untreated control. The average yield of the sugar beet crop grown in 2020 was 57.3 t/ha. This modest yield may, again, reflect an unirrigated crop grown on light-textured soil. In addition, to allow successful establishment of the subsequent cover crop, the sugar beet crop was harvested relatively early, and this would have limited yield potential. Whilst there were numerical differences associated with use of cover crops or amendments on yield and quality variates, these were not statistically significant.

Table 12. Effect of previous cover crop or organic amendment on yield of spring barley (2019-66) and sugar beet (2020-80). VCS Ltd, Illington, Norfolk

	Spring barley (Expt 2019-66)	Sugar beet (Expt 2020-80)			
	Grain yield at 15 % MC (t/ha)	Plant population (000/ha)	Clean beet yield (t/ha)	Sugar yield (t/ha)	Amino N (mg/100g)
Control	2.42	68.1	58.3	8.77	18.4
Cover crop	2.49	59.3	53.4	7.93	20.0
Amendment	2.67	68.0	60.3	9.06	17.1
Mean	2.53	65.1	57.3	8.59	18.5
S.E. (22 D.F.)	0.218	5.24	2.54	0.385	0.91

3.4. Soil data from unreplicated experiments

Through the course of the experimental program, measurements of key soil physical properties were made in the unreplicated (or limited replication) growers' comparisons. The purpose of the soil data was to examine the effects of soil organic amendment and/or use of cover crops on soil bulk density, porosity and water-stable aggregates and thereby start to better understand the mechanisms by which the treatment effect the growth and yield of crops in the rotation.

3.4.1. Materials and Method

3.4.1.1. Bulk density and porosity

In most experiments soil bulk density was measured using a "brick" corer (a steel box, 10 (d) x 10 (w) x 20 (l) cm). In use, the corer and a removable lid was placed on top of soil and hammered in until the edges of the corer were just level with the soil surface. Using a trowel or spade, sufficient soil surrounding the corer was carefully removed so that a steel plate could then be slid under the corer to retain the soil. The corer, lid and plate were then removed, and the content of the core placed into a labelled plastic bag which was then sealed. This core contained soil from 0-10 cm depth. For deeper cores (i.e. 10-20 cm), the process was repeated by placing the core immediately on top of where the initial core had been taken. For soil sampling potato ridges, the top of the ridge was carefully levelled using a trowel or spade before the core was taken. In some experiments soil cores were taken using smaller, cylindrical cores of c. 95 or 196 cm^3. However, the principal of coring was broadly similar.

Once back at Cambridge, the contents of the bags were emptied into aluminium trays which were then placed in drying oven. The soil samples were dried for c. 24 hours at 105 °C, and the weight of the dried soil recorded. Dry bulk density (g/cm^3) was then calculated by dividing the mass of the dried soil by the volume of the corer (2000 cm^3). Thus, if the mass of oven dried soil was 2500 g, then the dry bulk density would be 1.25 g/cm^3.

Porosity (defined as the fraction of the soil volume take up by the pore space) was estimated by assuming that the solid fraction of soil has a bulk density of 2.65 g/cm^3 (Marshall & Holmes 1979). Dividing, the dry mass of the soil by the density of soil solids gives the volume of solids from which porosity can be estimated. In the above example, the dry weight of soil was 2500 g and assuming a density of 2.65 g/cm^3 the volume of solids would be 943 cm^3. Since the volume of the original core was 2000 cm3, the porosity would be ((2000-943)/2000)*100 % = 52.9 %. The density of soil solids varies with soil organic matter content and mineralogy of the soil and thus a value of 2.65 g/cm^3 is an approximation. However, for comparing treatments on similar types within a field this approximation is unlikely to introduce significant bias.

3.4.1.2. Water stable aggregates

Measurement of the proportion of water stable aggregates (WSA) gives an indication of the stability of soil structure and its resilience to perturbation (e.g. by heavy rainfall events or irrigation). Soil with low WSAs is more likely to lose structure, increase in bulk density and form soil caps/crusts when stressed by intense rain or irrigation. The effect of organic amendments or cover crops on WSA was measured using an Eijkelkamp wet sieving apparatus. For each soil sample, four, air dried soils samples (c. 4 g) were accurately weighed into a duplicate 2.00 and 0.25 mm Eijkelkamp sieves. The soil samples were typically derived from the 'brick' bulk density cores described above with the WSA sub-samples being removed before oven-drying. Bulk densities weights were corrected for the weight of soil removed for WSA determination.

The sieves were then placed on the apparatus and then repeatedly immersed in distilled water for 180 (± 5) seconds at c. 0.5 cycles per second. The weight of the soil remaining on sieve was carefully transferred onto an aluminium tray and the soil was then oven dried as described above. The proportion of the soil remaining on the sieve indicates aggregates strength.

3.4.2. Results and discussion

Table 13 to Table 16 report the effects of organic amendments on key soil properties in replicated and randomized experiments on the farms of Platform members. Table 17 shows the effects of organic amendments and cover crops on soil properties in unreplicated “strip” trials. For experimental details see Table 1 and Table 2.

As might be expected, numeric difference in soil properties were found in several experiments however these differences were generally small and variable in direction. Summary data (Table 29) show that, collectively, organic amendments had no effect on soil bulk density or 2.00 or 0.25 mm water stable aggregates. Separating the amendments into ‘manures’ and more bulky ‘composts’ indicated that use of compost might be associated with small reductions in bulk density. Separation of amendment into type had no effect on WSAs. Realistically, cover crops had no effect on soil bulk density in either the 0-10 or 10-20 cm soil layers. Similarly, there was evidence in cover crops resulting in small increases in WSA at both depths. Based on these data, there was scant evidence that use of cover crops or organic amendments reduced soil bulk density or increased the resilience of soil aggregates to degradation by rainfall and irrigation. The 3.0 t/ha increase in tuber yield (Table 4) resulting from use of cover crops cannot be explained by these data. It is possible that, in these experiments, the beneficial effect of cover crops was brought about by effects at a greater depth than measured in these experiments.

Table 13. Effect of organic amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) at Greenwell Farms, Orford Walk (Expt 2017-5). Sampled on 29 June 17

Sampling Depth (cm)	Soil Property	Control	Compost	Duck manure	S.E.
0-10	Bulk density (g/cm^3)	1.11	1.04	0.99	0.029
	Porosity (%)	58.1	60.9	62.5	1.10
	WSA 2.00 mm	0.08	0.06	0.08	0.012
	WSA 0.25 mm	0.45	0.47	0.48	0.019
10-20	Bulk density (g/cm^3)	1.30	1.26	1.17	0.029
	Porosity (%)	51.0	52.3	56.0	1.07
20-30	Bulk density (g/cm^3)	1.37	1.37	1.28	0.022
	Porosity (%)	48.1	48.4	51.6	0.83

Table 14. Effect of spring applied green-waste compost (60 t/ha) on soil bulk density, porosity, and proportion of water stable aggregates (WSA) at B and C Oxnead 2 (Expt 2018-37) on 9 October 2017

Soil Property	Control	Compost in 2016	S.E.
Soil depth 0-10 cm			
Bulk density (g/cm^3)	1.44	1.46	0.022
Porosity (%)	46.7	44.9	0.85
WSA 2.00 mm	0.67	0.60	0.074
WSA 0.25 mm	0.71	0.62	0.065
Soil depth 10-20			
Bulk density (g/cm^3)	1.48	1.50	0.037
Porosity (%)	44.3	43.4	1.41
Soil depth 20-30			
Bulk density (g/cm^3)	1.43	1.47	0.026
Porosity (%)	46.1	44.4	0.99

Table 15. Effect of spring applied green-waste compost (60 t/ha) on soil bulk density, porosity, and proportion of water stable aggregates (WSA) at B and C Oxnead 2 (Expt 2018-37) on 16 October 2018

Soil Property	Control	Compost in 2016	Compost in 2016 & 2017	Compost in 2016, 2017 & 2018	S.E.
Soil depth 0-10 cm					
Bulk density (g/cm^3)	1.14	1.07	1.15	1.15	0.061
Porosity (%)	57.2	59.7	56.7	56.6	2.30
WSA 2.00 mm	0.48	0.50	0.50	0.46	0.052
WSA 0.25 mm	0.61	0.62	0.62	0.63	0.036
Soil depth 10-20					
Bulk density (g/cm^3)	1.20	1.22	1.24	1.14	0.059
Porosity (%)	54.7	54.0	53.3	57.0	2.19
Soil depth 20-30					
Bulk density (g/cm^3)	1.18	1.30	1.29	1.24	0.059
Porosity (%)	55.3	51.0	51.3	53.0	2.20

Table 16. Effect of single or multiple application of organic amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) at Elveden Selfsets (Expt 2018-38)

	Sampled 29 June 2018			Sampled 3 September 2018		
Soil Property	Muck 2016 & compost 2017	Compost 2017	S.E.	Muck 2016 & compost 2017	Compost 2017	S.E.
Soil depth 0-10 cm						
Bulk density (g/cm^3)	1.06	1.02	0.024	1.04	1.05	0.029
Porosity (%)	59.9	61.6	0.92	60.9	60.2	1.10
WSA 2.00 mm	0.18	0.20	0.016	0.26	0.30	0.053
WSA 0.25 mm	0.31	0.32	0.019	0.54	0.51	0.032
Soil depth 10-20						
Bulk density (g/cm^3)	1.11	1.10	0.051	1.12	1.12	0.029
Porosity (%)	58.2	58.5	1.94	57.7	57.9	1.14
Soil depth 20-30						
Bulk density (g/cm^3)	1.05	1.06	0.077			
Porosity (%)	60.5	59.9	2.51			

Table 17. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth 0-10	10-20	10-30
Expt 2017-3	Control (5)	Bulk density (g/cm^3)	1.05 ± 0.018	1.06 ± 0.019	1.12 ± 0.026
21 June 17	Cover Crop (5)	Bulk density (g/cm^3)	1.10 ± 0.014	1.14 ± 0.029	1.13 ± 0.020
	Control (5)	Porosity	60.4 ± 0.69	60.2 ± 0.70	57.7 ± 0.97
	Cover Crop (5)	Porosity	58.1 ± 0.52	57.2 ± 1.08	57.4 ± 0.75
Expt 2017-3	Control (4)	Bulk density (g/cm^3)	1.20 ± 0.032	1.17 ± 0.052	
21 June 17	Cover Crop (4)	Bulk density (g/cm^3)	1.08 ± 0.058	1.17 ± 0.024	
	Control (4)	Porosity	54.6 ± 1.19	56.0 ± 1.97	
	Cover Crop (4)	Porosity	59.4 ± 2.18	55.9 ± 0.88	
	Control (4)	WSA 2.00 mm	0.48 ± 0.046		
	Cover Crop (4)	WSA 2.00 mm	0.57 ± 0.045		
	Control (4)	WSA 0.25 mm	0.60 ± 0.028		
	Cover Crop (4)	WSA 0.25 mm	0.68 ± 0.026		
Expt 2017-7	Control (4)	Bulk density (g/cm^3)	1.18 ± 0.018	1.20 ± 0.044	1.23 ± 0.078
16 June 17	Cover Crop (4)	Bulk density (g/cm^3)	1.15 ± 0.022	1.17 ± 0.021	1.25 ± 0.070
	Control (4)	Porosity	55.6 ± 0.70	54.8 ± 1.65	53.8 ± 2.94
	Cover Crop (4)	Porosity	56.8 ± 0.83	56.0 ± 0.80	53.0 ± 2.62
Expt 2017-8	Control (4)	Bulk density (g/cm^3)	1.16 ± 0.050	1.36 ± 0.057	
4 October 17	Amendt1 (4)	Bulk density (g/cm^3)	1.24 ± 0.043	1.45 ± 0.026	
	Amend't 2 (4)	Bulk density (g/cm^3)	1.16 ± 0.070	1.46 ± 0.088	
	Control (4)	Porosity	56.3 ± 1.90	48.9 ± 2.15	
	Amend't 1 (4)	Porosity	53.1 ± 1.61	45.5 ± 0.98	
	Amend't 2 (4)	Porosity	56.4 ± 2.62	45.1 ± 3.30	
	Control (4)	WSA 2.00 mm	0.29 ± 0.048		
	Amend't 1 (4)	WSA 2.00 mm	0.28 ± 0.047		
	Amend't 2 (4)	WSA 2.00 mm	0.23 ± 0.071		
	Control (4)	WSA 0.25 mm	0.54 ± 0.027		
	Amend't 1 (4)	WSA 0.25 mm	0.50 ± 0.017		
	Amend't 2 (4)	WSA 0.25 mm	0.55 ± 0.051		

Table 18. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons (continued)

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth		
			0-10	10-20	10-30
Expt 2017-9	Control (6)	Bulk density (g/cm³)	1.10 ± 0.029	1.16 ± 0.050	1.19 ± 0.079
25 May 17	Cover Crop (6)	Bulk density (g/cm³)	1.06 ± 0.031	1.09 ± 0.047	1.15 ± 0.040
	Control (6)	Porosity	58.6 ± 1.10	56.3 ± 1.89	55.1 ± 3.00
	Cover Crop (6)	Porosity	59.9 ± 1.17	59.0 ± 1.78	56.6 ± 1.51
Expt 2017-9	Control (4)	Bulk density (g/cm³)	1.10 ± 0.021	1.12 ± 0.016	
2 Sept. 17	Cover Crop (4)	Bulk density (g/cm³)	1.10 ± 0.026	1.16 ± 0.006	
	Control (4)	Porosity	58.3 ± 0.81	57.8 ± 0.62	
	Cover Crop (4)	Porosity	58.5 ± 0.98	56.1 ± 0.21	
	Control (4)	WSA 2.00 mm	0.33 ± 0.098		
	Cover Crop (4)	WSA 2.00 mm	0.22 ± 0.034		
	Control (4)	WSA 0.25 mm	0.39 ± 0.054		
	Cover Crop (4)	WSA 0.25 mm	0.32 ± 0.046		
Expt 2017-10	Control (4)	Bulk density (g/cm³)	1.18 ± 0.030	1.24 ± 0.019	1.29 ± 0.033
28 July 17	Amendment (4)	Bulk density (g/cm³)	1.21 ± 0.050	1.25 ± 0.020	1.29 ± 0.020
	Control (4)	Porosity	55.3 ± 1.13	53.1 ± 0.71	51.2 ± 1.25
	Amendment (4)	Porosity	54.2 ± 1.89	52.8 ± 0.73	51.4 ± 0.77
Expt 2017-10	Control (4)	Bulk density (g/cm³)	1.24 ± 0.037	1.27 ± 0.015	
22 Sept. 17	Amendment (4)	Bulk density (g/cm³)	1.24 ± 0.016	1.29 ± 0.010	
	Control (4)	Porosity	53.3 ± 1.39	52.2 ± 0.58	
	Amendment (4)	Porosity	53.2 ± 0.60	51.2 ± 0.39	
	Control (4)	WSA 2.00 mm	0.02 ± 0.005		
	Amendment (4)	WSA 2.00 mm	0.06 ± 0.013		
	Control (4)	WSA 0.25 mm	0.49 ± 0.017		
	Amendment (4)	WSA 0.25 mm	0.54 ± 0.015		
Expt 2017-11	Control (4)	Bulk density (g/cm³)	1.12 ± 0.053	1.10 ± 0.047	1.15 ± 0.053
25 May 17	Cover Crop (5)	Bulk density (g/cm³)	1.00 ± 0.026	1.04 ± 0.052	1.07 ± 0.054
	Control (4)	Porosity	57.6 ± 2.00	58.6 ± 1.79	56.4 ± 1.97
	Cover Crop (5)	Porosity	62.3 ± 0.98	60.7 ± 1.94	59.7 ± 2.04

Table 19. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons (continued)

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth		
			0-10	10-20	10-30
Expt 2017-11	Control (6)	Bulk density (g/cm^3)	1.09 ± 0.036	1.23 ± 0.060	
22 Sept. 17	Cover Crop (6)	Bulk density (g/cm^3)	1.08 ± 0.041	1.21 ± 0.052	
	Control (6)	Porosity	59.0 ± 1.37	53.6 ± 2.27	
	Cover Crop (6)	Porosity	59.3 ± 1.54	54.3 ± 1.94	
	Control (6)	WSA 2.00 mm	0.72 ± 0.030		
	Cover Crop (6)	WSA 2.00 mm	0.58 ± 0.071		
	Control (6)	WSA 0.25 mm	0.77 ± 0.025		
	Cover Crop (6)	WSA 0.25 mm	0.73 ± 0.048		
Expt 2017-12	Control (4)	Bulk density (g/cm^3)	1.29 ± 0.045	1.30 ± 0.042	1.28 ± 0.049
22 May 17	Cover Crop (5)	Bulk density (g/cm^3)	1.26 ± 0.043	1.24 ± 0.059	1.26 ± 0.062
	Control (4)	Porosity	51.4 ± 1.68	51.0 ± 1.57	51.5 ± 1.85
	Cover Crop (5)	Porosity	52.4 ± 1.64	53.3 ± 2.24	52.5 ± 2.32
Expt 2017-12	Control (6)	Bulk density (g/cm^3)	1.17 ± 0.018	1.25 ± 0.039	
19 Sept. 17	Cover Crop (6)	Bulk density (g/cm^3)	1.24 ± 0.040	1.32 ± 0.039	
	Control (6)	Porosity	55.9 ± 0.68	53.0 ± 1.48	
	Cover Crop (6)	Porosity	53.1 ± 1.51	50.1 ± 1.46	
	Control (6)	WSA 2.00 mm	0.22 ± 0.031		
	Cover Crop (6)	WSA 2.00 mm	0.32 ± 0.056		
	Control (6)	WSA 0.25 mm	0.57 ± 0.030		
	Cover Crop (6)	WSA 0.25 mm	0.62 ± 0.032		
Expt 2017-14	Control (6)	Bulk density (g/cm^3)	1.05 ± 0.018	1.14 ± 0.032	1.22 ± 0.037
20 July 17	Amendment (6)	Bulk density (g/cm^3)	0.95 ± 0.020	1.07 ± 0.032	1.25 ± 0.031
	Control (6)	Porosity	60.4 ± 0.68	56.9 ± 1.19	54.1 ± 1.40
	Amendment (6)	Porosity	64.1 ± 0.75	59.6 ± 1.22	52.8 ± 1.18
	Control (6)	WSA 2.00 mm	0.10 ± 0.026		
	Amendment (6)	WSA 2.00 mm	0.09 ± 0.012		
	Control (6)	WSA 0.25 mm	0.46 ± 0.030		
	Amendment (6)	WSA 0.25 mm	0.53 ± 0.041		
Expt 2017-15	Amendment (4)	Bulk density (g/cm^3)	1.17 ± 0.053	1.24 ± 0.066	1.34 ± 0.064
30 July 15	Cover Crop (4)	Bulk density (g/cm^3)	1.06 ± 0.081	1.14 ± 0.124	1.16 ± 0.076
	Amendment (4)	Porosity	55.9 ± 2.00	53.1 ± 2.48	49.3 ± 2.43
	Cover Crop (4)	Porosity	60.1 ± 3.06	57.2 ± 4.67	56.4 ± 2.89

Table 20. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons (continued)

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth		
			0-10	10-20	10-30
Expt 2017-15	Amendment (4)	Bulk density (g/cm^3)	1.04 ± 0.087	1.25 ± 0.073	
6 Sept 17	Cover Crop (4)	Bulk density (g/cm^3)	1.12 ± 0.051	1.23 ± 0.064	
	Amendment (4)	Porosity	60.7 ± 3.30	53.0 ± 2.76	
	Cover Crop (4)	Porosity	57.8 ± 1.93	53.5 ± 2.43	
	Amendment (4)	WSA 2.00 mm	0.19 ± 0.032		
	Cover Crop (4)	WSA 2.00 mm	0.25 ± 0.015		
	Amendment (4)	WSA 0.25 mm	0.37 ± 0.024		
	Cover Crop (4)	WSA 0.25 mm	0.39 ± 0.031		
Expt 2017-16	Control (4)	Bulk density (g/cm^3)	1.26 ± 0.113	1.21 ± 0.091	
6 Sept. 17	Amendment (4)	Bulk density (g/cm^3)	1.36 ± 0.063	1.29 ± 0.078	
	Control (4)	Porosity	52.6 ± 4.27	54.4 ± 3.41	
	Amendment (4)	Porosity	48.8 ± 2.40	51.3 ± 2.95	
	Control (4)	WSA 2.00 mm	0.04 ± 0.040		
	Amendment (4)	WSA 2.00 mm	0.07 ± 0.037		
	Control (4)	WSA 0.25 mm	0.52 ± 0.009		
	Amendment (4)	WSA 0.25 mm	0.51 ± 0.012		
Expt 2017-21	BioS (4)	Bulk density (g/cm^3)	1.34 ± 0.010	1.35 ± 0.022	
1 Aug 17*	BioR (4)	Bulk density (g/cm^3)	1.32 ± 0.020	1.41 ± 0.008	
	CCFR	Bulk density (g/cm^3)	1.29 ± 0.035	1.36 ± 0.011	
	BOPhCC	Bulk density (g/cm^3)	1.32 ± 0.016	1.37 ± 0.011	
	FRV	Bulk density (g/cm^3)	1.33 ± 0.014	1.37 ± 0.012	
	Control	Bulk density (g/cm^3)	1.34 ± 0.021	1.39 ± 0.020	
	BioS (4)	Porosity	49.5 ± 0.36	49.0 ± 0.82	
	BioR (4)	Porosity	50.0 ± 0.73	47.0 ± 0.32	
	CCFR	Porosity	51.2 ± 1.34	48.7 ± 0.40	
	BOPhCC	Porosity	50.1 ± 0.60	48.4 ± 0.40	
	FRV	Porosity	49.9 ± 0.54	48.3 ± 0.46	
	Control	Porosity	49.3 ± 0.79	47.4 ± 0.74	

Table 21. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons (continued)

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth		
			0-10	10-20	10-30
Expt 2017-22	BioS (4)	Bulk density (g/cm^3)	1.35 ± 0.010	1.37 ± 0.010	
21 Aug 17*	BioR (4)	Bulk density (g/cm^3)	1.31 ± 0.010	1.37 ± 0.002	
	CCFR	Bulk density (g/cm^3)	1.32 ± 0.016	1.36 ± 0.019	
	BOPhCC	Bulk density (g/cm^3)	1.34 ± 0.013	1.37 ± 0.012	
	FRV	Bulk density (g/cm^3)	1.26 ± 0.021	1.29 ± 0.006	
	Control	Bulk density (g/cm^3)	1.28 ± 0.016	1.37 ± 0.024	
	BioS (4)	Porosity	49.1 ± 0.39	48.2 ± 0.37	
	BioR (4)	Porosity	50.8 ± 0.36	48.2 ± 0.09	
	CCFR	Porosity	50.4 ± 0.63	48.8 ± 0.72	
	BOPhCC	Porosity	49.6 ± 0.49	48.2 ± 0.46	
	FRV	Porosity	52.3 ± 0.80	51.3 ± 0.22	
	Control	Porosity	51.6 ± 0.60	48.5 ± 0.91	
Expt-2018-25	Control (4)	Bulk density (g/cm^3)	1.09 ± 0.012	1.09 ± 0.026	
3 July 2018	Control-1 (4)	Bulk density (g/cm^3)	1.05 ± 0.031	1.11 ± 0.010	
	Cover Crop (4)	Bulk density (g/cm^3)	0.99 ± 0.030	1.05 ± 0.028	
	Cover Crop 1 (4)	Bulk density (g/cm^3)	0.94 ± 0.039	1.02 ± 0.017	
	Control (4)	Porosity	58.7 ± 0.44	58.9 ± 0.98	
	Control-1 (4)	Porosity	60.4 ± 1.18	58.0 ± 0.39	
	Cover Crop (4)	Porosity	62.5 ± 1.15	60.3 ± 1.05	
	Cover Crop 1 (4)	Porosity	64.6 ± 1.45	61.5 ± 0.66	
	Control (4)	WSA 2.00 mm	0.78 ± 0.048		
	Control-1 (4)	WSA 2.00 mm	0.53 ± 0.094		
	Cover Crop (4)	WSA 2.00 mm	0.55 ± 0.095		
	Cover Crop 1 (4)	WSA 2.00 mm	0.64 ± 0.053		
	Control (4)	WSA 0.25 mm	0.90 ± 0.011		
	Control-1 (4)	WSA 0.25 mm	0.83 ± 0.009		
	Cover Crop (4)	WSA 0.25 mm	0.79 ± 0.026		
	Cover Crop 1 (4)	WSA 0.25 mm	0.81 ± 0.020		
Expt 2018-26	Control (3)	WSA 2.00 mm	0.14 ± 0.056		
5 June 2018	Amendment (3)	WSA 2.00 mm	0.09 ± 0.027		
	Control (3)	WSA 0.25 mm	0.41 ± 0.012		
	Amendment (3)	WSA 0.25 mm	0.43 ± 0.009		

Table 22. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons (continued)

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth		
			0-10	10-20	10-30
Expt 2018-27	Control (3)	WSA 2.00 mm	0.15 ± 0.092		
5 June 2018	Amendment (3)	WSA 2.00 mm	0.12 ± 0.040		
	Cover Crop (3)	WSA 2.00 mm	0.07 ± 0.012		
	Control (3)	WSA 0.25 mm	0.51 ± 0.061		
	Amendment (3)	WSA 0.25 mm	0.49 ± 0.032		
	Cover Crop 3	WSA 0.25 mm	0.44 ± 0.012		
Expt 2018-28	Control (5)	Bulk density (g/cm^3)	1.22 ± 0.032	1.24 ± 0.019	
3 July 2018	Cover Crop (5)	Bulk density (g/cm^3)	1.18 ± 0.016	1.25 ± 0.035	
	Control (5)	Porosity	54.0 ± 1.18	53.3 ± 0.72	
	Cover Crop (5)	Porosity	55.7 ± 0.61	52.7 ± 1.33	
	Control (5)	WSA 2.00 mm	0.13 ± 0.016		
	Cover Crop (5)	WSA 2.00 mm	0.13 ± 0.014		
	Control (5)	WSA 0.25 mm	0.62 ± 0.019		
	Cover Crop (5)	WSA 0.25 mm	0.61 ± 0.025		
Expt 2018-29	Control (3)	Bulk density (g/cm^3)	1.09 ± 0.074	0.93 ± 0.047	
11 Apr 18	CC Ploughed (3)	Bulk density (g/cm^3)	1.18 ± 0.050	1.21 ± 0.143	
	CC Grazed (3)	Bulk density (g/cm^3)	1.10 ± 0.090	0.96 ± 0.045	
	Control (3)	Porosity	59.1 ± 2.77	64.9 ± 1.77	
	CC Ploughed (3)	Porosity	55.2 ± 1.85	54.3 ± 5.40	
	CC Grazed (3)	Porosity	58.6 ± 3.40	63.7 ± 1.69	
Expt 2018-29	Control (1)	Bulk density (g/cm^3)	0.97	1.09	1.12
11 Apr 18	CC Ploughed (1)	Bulk density (g/cm^3)	0.84	0.99	1.03
	CC Grazed (1)	Bulk density (g/cm^3)	0.86	0.92	1.02
	Control (1)	Porosity	63.5	58.8	57.9
	CC Ploughed (1)	Porosity	68.3	62.8	61.3
	CC Grazed (1)	Porosity	67.7	65.2	61.7
Expt 2018-33	Chicken FYM	Bulk density (g/cm^3)	1.22 ± 0.016	1.22 ± 0.029	
5 Aug 2018	Compost (4)	Bulk density (g/cm^3)	1.23 ± 0.051	1.31 ± 0.017	
	Chicken FYMe	Porosity	54.2 ± 0.60	54.2 ± 1.10	
	Compost (4)	Porosity	53.4 ± 1.94	50.7 ± 0.64	

Table 23. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons (continued)

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth		
			0-10	10-20	10-30
Expt 2018-35	Control (4)	Bulk density (g/cm^3)	1.18 ± 0.026	1.26 ± 0.028	
23 May 2018	Amendment (4)	Bulk density (g/cm^3)	1.17 ± 0.028	1.30 ± 0.042	
	Control (4)	Porosity (%)	55.5 ± 0.98	52.6 ± 1.08	
	Amendment (4)	Porosity (%)	55.8 ± 1.05	51.0 ± 1.60	
Expt 2018-36	Control (4)	Bulk density (g/cm^3)	1.06 ± 0.030	1.10 ± 0.016	
22 June 18	Cereal (4)	Bulk density (g/cm^3)	1.07 ± 0.035	1.11 ± 0.028	
	Biofumigant (4)	Bulk density (g/cm^3)	1.00 ± 0.007	1.00 ± 0.039	
	Control (4)	Porosity (%)	60.1 ± 1.11	58.7 ± 0.61	
	Cereal (4)	Porosity (%)	59.6 ± 1.33	58.1 ± 1.04	
	Biofumigant (4)	Porosity (%)	62.4 ± 0.27	62.0 ± 1.45	
	Control (4)	WSA 2.00 mm	0.29 ± 0.035		
	Cereal (4)	WSA 2.00 mm	0.48 ± 0.054		
	Biofumigant (4)	WSA 2.00 mm	0.55 ± 0.065		
	Control (4)	WSA 0.25 mm	0.50 ± 0.019		
	Cereal (4)	WSA 0.25 mm	0.65 ± 0.050		
	Biofumigant (4)	WSA 0.25 mm	0.70 ± 0.053		
Expt 2018-39	Control (5)	Bulk density (g/cm^3)	1.12 ± 0.042	1.19 ± 0.018	
3 Sept. 2018	Amend't-1 (5)	Bulk density (g/cm^3)	1.11 ± 0.047	1.23 ± 0.015	
	Amend't-2 (5)	Bulk density (g/cm^3)	1.18 ± 0.026	1.18 ± 0.019	
	Control (5)	Porosity (%)	57.7 ± 1.58	54.9 ± 0.70	
	Amend't-1 (5)	Porosity (%)	58.1 ± 1.79	53.7 ± 0.56	
	Amend't-2 (5)	Porosity (%)	55.5 ± 0.98	55.4 ± 0.71	
	Control (5)	WSA 2.00 mm	0.05 ± 0.008		
	Amend't-1 (5)	WSA 2.00 mm	0.06 ± 0.012		
	Amend't-2 (5)	WSA 2.00 mm	0.03 ± 0.005		
	Control (5)	WSA 0.25 mm	0.34 ± 0.010		
	Amend't-1 (5)	WSA 0.25 mm	0.36 ± 0.008		
	Amend't-2 (5)	WSA 0.25 mm	0.34 ± 0.012		

Table 24. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons (continued)

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth 0-10	10-20	10-30
Expt 2018-40	Control	Bulk density (g/cm^3)	1.62 ± 0.042	1.72 ± 0.055	
24 Aug 18	Compost	Bulk density (g/cm^3)	1.64 ± 0.073	1.75 ± 0.071	
	Pig FYM	Bulk density (g/cm^3)	1.74 ± 0.069	1.55 ± 0.073	
	Control	Porosity (%)	39.0 ± 1.59	35.2 ± 2.09	
	Compost	Porosity (%)	38.2 ± 2.76	33.7 ± 2.68	
	Pig FYM	Porosity (%)	34.4 ± 2.58	41.6 ±2.76	
Expt 2018-42	Control (3)	Bulk density (g/cm^3)	1.48 ± 0.034	1.51 ± 0.007	
24 Aug 2018*	CCBO (3)	Bulk density (g/cm^3)	1.44 ± 0.008	1.46 ± 0.009	
	BOPhCC (3)	Bulk density (g/cm^3)	1.45 ± 0.035	1.47 ± 0.058	
	S. Radish (3)	Bulk density (g/cm^3)	1.45 ± 0.058	1.43 ± 0.054	
	BioS (3)	Bulk density (g/cm^3)	1.52 ± 0.049	1.44 ± 0.017	
	Control (3)	Porosity (%)	44.2 ± 1.30	42.9 ± 0.23	
	CCBO (3)	Porosity (%)	45.5 ± 0.29	45.0 ± 0.32	
	BOPhCC (3)	Porosity (%)	45.3 ± 1.30	44.5 ± 2.20	
	S. Radish (3)	Porosity (%)	45.3 ± 2.18	46.0 ± 2.04	
	BioS (3)	Porosity (%)	42.8 ± 1.87	45.7 ± 0.63	
	Control (3)	WSA 2.00 mm	0.22 ± 0.040		
	CCBO (3)	WSA 2.00 mm	0.20 ± 0.044		
	BO, Ph & CC (3)	WSA 2.00 mm	0.20 ± 0.039		
	S. Radish (3)	WSA 2.00 mm	0.20 ± 0.033		
	BioS (3)	WSA 2.00 mm	0.18 ± 0.038		
	Control (3)	WSA 0.25 mm	0.49 ± 0.020		
	CCBO (3)	WSA 0.25 mm	0.49 ± 0.019		
	BOPhCC (3)	WSA 0.25 mm	0.54 ± 0.012		
	S. Radish (3)	WSA 0.25 mm	0.49 ± 0.010		
	BioS (3)	WSA 0.25 mm	0.50 ± 0.000		

Table 25. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons (continued)

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth		
			0-10	10-20	10-30
Expt 2018-44	Control (3)	Bulk density (g/cm^3)	1.20 ± 0.008	1.22 ± 0.019	
24 Aug 2018*	CCBO (3)	Bulk density (g/cm^3)	1.17 ± 0.024	1.24 ± 0.015	
	BOPhCC (3)	Bulk density (g/cm^3)	1.23 ± 0.017	1.25 ± 0.003	
	S. Radish (3)	Bulk density (g/cm^3)	1.17 ± 0.025	1.25 ± 0.011	
	BioS (3)	Bulk density (g/cm^3)	1.19 ± 0.016	1.25 ± 0.012	
	Control (3)	Porosity (%)	54.8 ± 0.30	54.0 ± 0.74	
	CCBO (3)	Porosity (%)	56.0 ± 0.92	53.0 ± 0.56	
	BOPhCC (3)	Porosity (%)	53.6 ± 0.64	52.9 ± 0.12	
	S. Radish (3)	Porosity (%)	56.0 ± 0.91	52.7 ± 0.38	
	BioS (3)	Porosity (%)	55.3 ± 0.59	53.0 ± 0.42	
	Control (3)	WSA 2.00 mm	0.22 ± 0.033		
	CCBO (3)	WSA 2.00 mm	0.16 ± 0.026		
	BOPhCC (3)	WSA 2.00 mm	0.28 ± 0.052		
	S. Radish (3)	WSA 2.00 mm	0.19 ± 0.010		
	BioS (3)	WSA 2.00 mm	0.19 ± 0.023		
	Control (3)	WSA 0.25 mm	0.56 ± 0.029		
	CCBO (3)	WSA 0.25 mm	0.57 ± 0.030		
	BOPhCC (3)	WSA 0.25 mm	0.56 ± 0.015		
	S. Radish (3)	WSA 0.25 mm	0.50 ± 0.010		
	BioS (3)	WSA 0.25 mm	0.47 ± 0.006		
Expt 2018-45	Control (4)	Bulk density (g/cm^3)	1.06 ± 0.030	1.10 ± 0.016	
22 June 18	Cereal (4)	Bulk density (g/cm^3)	1.07 ± 0.035	1.11 ± 0.028	
	Biofumigant (4)	Bulk density (g/cm^3)	1.00 ± 0.007	1.01 ± 0.039	
	Control (4)	Porosity (%)	60.1 ± 1.11	58.7 ± 0.61	
	Cereal (4)	Porosity (%)	59.6 ± 1.33	58.1 ± 1.04	
	Biofumigant (4)	Porosity (%)	62.4 ± 0.27	62.0 ± 1.45	
	Control (4)	WSA 2.00 mm	0.29 ± 0.035		
	Cereal (4)	WSA 2.00 mm	0.48 ± 0.054		
	Biofumigant (4)	WSA 2.00 mm	0.55 ± 0.065		
	Control (4)	WSA 0.25 mm	0.50 ± 0.019		
	Cereal (4)	WSA 0.25 mm	0.65 ± 0.050		
	Biofumigant (4)	WSA 0.25 mm	0.70 ± 0.053		

Table 26. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons (continued)

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth		
			0-10	10-20	10-30
Expt 2019-56	Control (4)	Bulk density (g/cm^3)	1.14 ± 0.046	1.32 ± 0.020	
7 Aug 2019	Amendment (4)	Bulk density (g/cm^3)	1.07 ± 0.075	1.13 ± 0.040	
	Control (4)	Porosity	57.0 ± 1.71	50.8 ± 0.74	
	Amendment (4)	Porosity	59.7 ± 2.82	57.2 ± 1.52	
Expt 2019-63	Control (4)	Bulk density (g/cm^3)	1.17 ± 0.047	1.22 ± 0.023	
12 Aug. 2019	Amendment (4)	Bulk density (g/cm^3)	1.21 ± 0.029	1.21 ± 0.048	
	Control (4)	Porosity	56.0 ± 1.77	53.8 ± 0.87	
	Amendment (4)	Porosity	54.4 ± 1.08	54.3 ± 1.80	
	Control (4)	WSA 2.00 mm	0.03 ± 0.010	0.03 ± 0.005	
	Amendment (4)	WSA 2.00 mm	0.04 ± 0.006	0.03 ± 0.013	
	Control (4)	WSA 0.25 mm	0.58 ± 0.035	0.58 ± 0.020	
	Amendment (4)	WSA 0.25 mm	0.60 ± 0.018	0.58 ± 0.014	
Expt 2019-67	Control (4)	Bulk density (g/cm^3)	1.01 ± 0.025	1.10 ± 0.036	
21 Aug. 2019	Cover Crop (4)	Bulk density (g/cm^3)	0.97 ± 0.029	1.03 ± 0.045	
	Control (4)	Porosity	61.8 ± 0.96	58.3 ± 1.36	
	Cover Crop (4)	Porosity	63.4 ± 1.08	61.2 ± 1.71	
	Control (4)	WSA 2.00 mm	0.21 ± 0.065	0.41 ± 0.064	
	Cover Crop (4)	WSA 2.00 mm	0.26 ± 0.027	0.31 ± 0.094	
	Control (4)	WSA 0.25 mm	0.36 ± 0.038	0.47 ± 0.074	
	Cover Crop (4)	WSA 0.25 mm	0.43 ± 0.026	0.35 ± 0.048	
Expt 2019-68	Control (3)	WSA 2.00 mm	0.50 ± 0.047		
26 Sep. 2019	Amendment (3)	WSA 2.00 mm	0.39 ± 0.100		
	Control (3)	WSA 0.25 mm	0.55 ± 0.064		
	Amendment (3)	WSA 0.25 mm	0.44 ± 0.047		
Expt 2020-71	Control (4)	Bulk density (g/cm^3)	1.01 ± 0.024	1.10 ± 0.036	
8 Sept 2020	Cover Crop (4)	Bulk density (g/cm^3)	0.97 ± 0.029	1.04 ± 0.044	
	Control (4)	Porosity	61.9 ± 0.91	58.4 ± 1.34	
	Cover Crop (4)	Porosity	63.3 ± 1.09	60.9 ± 1.66	

Table 27. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons (continued)

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth 0-10	10-20	10-30
Expt 2020-76	Control (4)	Bulk density (g/cm^3)	1.03 ± 0.022	1.10 ± 0.027	
8 Sept 2020	Cover Crop (4)	Bulk density (g/cm^3)	1.01 ± 0.018	0.99 ± 0.027	
	Control (4)	Porosity	61.1 ± 0.81	58.5 ± 1.02	
	Cover Crop (4)	Porosity	61.9 ± 0.67	62.8 ± 1.04	
	Control (4)	WSA 2.00 mm	0.03 ± 0.006	0.08 ± 0.031	
	Cover Crop (4)	WSA 2.00 mm	0.16 ± 0.015	0.22 ± 0.027	
	Control (4)	WSA 0.25 mm	0.78 ± 0.051	0.79 ± 0.041	
	Cover Crop (4)	WSA 0.25 mm	0.83 ± 0.022	0.80 ± 0.028	
Expt 2020-79	Control (4)	Bulk density (g/cm^3)	1.24 ± 0.019	1.41 ± 0.069	
3 Sept 2020	Cover Crop (4)	Bulk density (g/cm^3)	0.98 ± 0.070	1.20 ± 0.057	
	Control (4)	Porosity	53.3 ± 0.72	46.7 ± 2.62	
	Cover Crop (4)	Porosity	63.2 ± 2.66	54.7 ± 2.12	
	Control (4)	WSA 2.00 mm	0.06 ± 0.021	0.10 ± 0.031	
	Cover Crop (4)	WSA 2.00 mm	0.04 ± 0.012	0.13 ± 0.041	
	Control (4)	WSA 0.25 mm	0.26 ± 0.060	0.24 ± 0.081	
	Cover Crop (4)	WSA 0.25 mm	0.23 ± 0.064	0.32 ± 0.051	
Expt 2020-82	Control (4)	Bulk density (g/cm^3)	0.94 ± 0.009	0.94 ± 0.014	
30 Sept. 20	Cover Crop (4)	Bulk density (g/cm^3)	0.93 ± 0.011	0.90 ± 0.020	
	Control (4)	Porosity	64.6 ± 0.33	64.5 ± 0.52	
	Cover Crop (4)	Porosity	64.7 ± 0.44	65.9 ± 0.75	
	Control (4)	WSA 2.00 mm	0.12 ± 0.021	0.12 ± 0.037	
	Cover Crop (4)	WSA 2.00 mm	0.12 ± 0.033	0.14 ± 0.043	
	Control (4)	WSA 0.25 mm	0.81 ± 0.004	0.84 ± 0.028	
	Cover Crop (4)	WSA 0.25 mm	0.80 ± 0.008	0.85 ± 0.033	
Expt 2020-83	Control (4)	Bulk density (g/cm^3)	1.12 ± 0.026	0.99 ± 0.030	
30 Sept. 20	Cover Crop (4)	Bulk density (g/cm^3)	0.99 ± 0.030	1.03 ± 0.011	
	Control (4)	Porosity	57.9 ± 0.96	62.7 ± 1.16	
	Cover Crop (4)	Porosity	62.7 ± 1.16	61.2 ± 0.41	
	Control (4)	WSA 2.00 mm	0.07 ± 0.010	0.05 ± 0.024	
	Cover Crop (4)	WSA 2.00 mm	0.05 ± 0.024	0.05 ± 0.014	
	Control (4)	WSA 0.25 mm	0.68 ± 0.019	0.79 ± 0.019	
	Cover Crop (4)	WSA 0.25 mm	0.79 ± 0.019	0.84 ± 0.016	

Table 28. Effect of cover crop or amendments on soil bulk density, porosity, and proportion of water stable aggregates (WSA) in unreplicated 'strip' comparisons (continued)

Experiment and sample date	Treatment (and number of samples)	Variate	Soil Depth		
			0-10	10-20	10-30
Expt 2020-85	Control (4)	Bulk density (g/cm^3)	1.18 ± 0.005	1.28 ± 0.028	
6 Oct 2020	Amendment (4)	Bulk density (g/cm^3)	1.06 ± 0.051	1.16 ± 0.025	
	Control (4)	Porosity	55.6 ± 0.20	51.8 ± 1.07	
	Amendment (4)	Porosity	60.1 ± 1.93	56.3 ± 0.94	
	Control (4)	WSA 2.00 mm	0.02 ± 0.005	0.03 ± 0.009	
	Amendment (4)	WSA 2.00 mm	0.05 ± 0.016	0.09 ± 0.038	
	Control (4)	WSA 0.25 mm	0.74 ± 0.033	0.65 ± 0.041	
	Amendment (4)	WSA 0.25 mm	0.65 ± 0.034	0.58 ± 0.027	
Expt 2020-92	Defol.-Early (2)	Bulk density (g/cm^3)	1.03 ± 0.056	1.01 ± 0.066	
14 Oct. 2020	Defol.-Late (2)	Bulk density (g/cm^3)	0.96 ± 0.052	1.02 ± 0.054	
	Defol.-Early (2)	Porosity	61.0 ± 2.10	61.9 ± 2.50	
	Defol.-Late (2)	Porosity	64.0 ± 1.92	61.4 ± 2.00	
	Defol.-Early (2)	WSA 2.00 mm	0.09 ± 0.005	0.16 ± 0.050	
	Defol.-Late (2)	WSA 2.00 mm	0.30 ± 0.110	0.10 ± 0.010	
	Defol.-Early (2)	WSA 0.25 mm	0.33 ± 0.065	0.43 ± 0.020	
	Defol.-Late (2)	WSA 0.25 mm	0.50 ± 0.065	0.38 ± 0.020	

* Treatment codes for Experiments 21 & 22: BioS, Bio-fumigant Summer Mix; BioR, Bio-Fumigant Radish; CCFR, Crimson Clover & Fodder Rye; BOPhCC, Black Oat, Phacelia and Crimson Clover; FRV, Forage Rye and Vetch

* Treatment codes for Experiments 42 & 44 CCBO, Crimson Clover and Black Oat; BOPhCC, Black Oat, Phacelia and Crimson Clover; S. Radish, Siletina Radish; BioS, Biofumigant Summer Mix.

Table 29. Summary of effect of amendment or cover crops on soil bulk density and water stable aggregates (WSA) on a 2.00 or 0.25 mm mesh.

Variate	Treatment	Number of observations	Soil Depth	
			0-10	10-20
Bulk density	Control	19	1.21 ± 0.031	1.29 ± 0.034
	All amendments	19	1.21 ± 0.038	1.28 ± 0.032
Bulk density	Control	13	1.22 ± 0.038	1.29 ± 0.044
	Manures	13	1.24 ± 0.050	1.29 ± 0.032
Bulk density	Control	8	1.23 ± 0.069	1.34 ± 0.065
	Composts	8	1.20 ± 0.082	1.30 ± 0.079
WSA 2.00 mm	Control	17	0.27 ± 0.056	
	All amendments	17	0.26 ± 0.055	
	Control	15	0.26 ± 0.056	
	Manures	15	0.25 ± 0.056	
	Control	5	0.24 ± 0.116	
	Composts	5	0.20 ± 0.105	
WSA 0.25 mm	Control	17	0.53 ± 0.031	
	All amendments	17	0.53 ± 0.027	
	Control	15	0.53 ± 0.033	
	Manures	15	0.52 ± 0.030	
	Control	5	0.49 ± 0.055	
	Composts	5	0.50 ± 0.045	
Bulk density	Control	28 or 24*	1.15 ± 0.027	1.17 ± 0.029
	All cover crops	28 or 24*	1.12 ± 0.032	1.15 ± 0.029
WSA 2.00 mm	Control	19 or 5*	0.32 ± 0.054	0.15 ± 0.066
	All cover crops	19 or 5*	0.34 ± 0.050	0.17 ± 0.044
WSA 0.25 mm	Control	19 or 5*	0.61 ± 0.038	0.63 ± 0.117
	All cover crops	19 or 5*	0.63 ± 0.038	0.63 ± 0.122

* Smaller number of observations at 10-20 cm depth

4. DEVELOPMENT OF A SOIL ORGANIC MATTER MODEL

4.1. Summary

4.1.1. Aim

To devise optimal strategies that take account of how quickly (in years of application) yields build up with organic amendments and how long these benefits persist. This has been investigated with models and data from Rothamsted Research.

4.1.2. Methodology

The idea of a nutrient response curve was extended to include more than a single nutrient input and the effect of yield-enhancing factors such as organic matter that endure for more than one year. Such response curves are then treated analytically to develop economically optimum applications and in the case of organic matter economically optimal strategies over time. A simple static case is developed first, and this is shown to be equivalent to the well-known Break-Even Ratio (BER) used in nitrogen fertiliser guidance (AHDB Nutrient Management Guide (RB209)). The technique of optimal control was then employed to deduce dynamic strategies where the application of an amendment may change from year to year and where different time frames may be of interest.

4.1.3. Key findings

Because the methodology can appear complex, rules-of-thumb were inferred for an equilibrium level of yield-enhancement rather like the equilibrium level of organic carbon that builds up over several years. This yield-enhancing power of organic matter is somewhat variable and probably does not persist in soil as long as the organic matter from which it derives. In contrast to earlier work, it appears beneficial to apply amendments at a constant rate for much of the timeframe of interest but begin with a large application to raise the fertility as much as possible as soon as possible. Amendments should be approximately halved three years before the end of the period of interest and reduced to zero for the final two years of any period of interest.

4.1.4. Practical recommendations

If intending to apply organic matter, the optimum strategy is to apply initially at a rate close to the rule-of-thumb equilibrium, thereafter at a much lower rate that depends partly on the length of time (years) that amendment will continue. Amendment can be reduced greatly in the last 3 years. These conclusions depend on the persistence of the yield-enhancing power of organic matter in soil. This power was found to decline rapidly in a sandy soil, but less so in a silty clay loam soil. Current guidance for nitrogen fertiliser application has been developed over many years and on many different crops. It would be very expensive to embark upon a similar programme of data collection for organic amendments. However, it may be possible to relate the change in yield-enhancing power to the build-up and decline of organic matter in soil itself. If so, a small series of trials similar to the ones discussed in this report but on a range of soil types could establish how congruent OM dynamics and yield-enhancement are with the view to using the large amounts of information on the former to infer the latter.

An alternative to large scale experimental trials, would be for farmers to apply OM to strips in their fields for two or three years and follow the increase and decline of combine yields relative to the rest of the field. In this way as it is possible to infer parameters that describe an economically optimal strategy for managing organic matter amendments. As such a procedure could take up to 10 years to provide a clear-cut result, a farmer would almost certainly want to begin amendment elsewhere but be guided by results as they emerge from these on-farm trials.

4.2. Introduction

Organic amendments appear to increase yield (HGCA-2012-3787) and work elsewhere has assessed how long increases in yield are sustained once amendment ceases (SARIC NE/M016714/1). The next logical step is to devise optimal strategies that take account of how quickly (in years of application) yields build up with amendments and how long these benefits persist. Amendments such as manure or even compost are likely to be in short supply. Initial results using mathematical modelling at Rothamsted suggest that applications should be concentrated on fields most likely to show a benefit for two or three years but that additions can be reduced and made periodically afterwards. Two further issues warrant investigation. If amendments are to be made periodically it is not clear (1) how large the addition should be or (2) whether the same addition should be made each year or whether this should vary.

Nutrient response curves (George, 1984) are in common use to infer guidance for a wide range of crops (AHDB). However, George's linear plus exponential (lexp) model does not extend readily to include more than a single input or the effect of nutrients or a yield-enhancing factor such as organic matter that endure for more than one year. Greenwood (1971) worked with a reciprocal curve, and it seemed useful to work with this as well as develop an extension for the lexp model to analyse the response of yields to multiple nutrients over more than a single year. Such response curves can then be treated analytically to develop economically optimum applications and in the case of organic matter economically optimal strategies over time.

4.3. Materials and Methods

4.3.1. The Rothamsted Research datasets

4.3.1.1. The Woburn manuring experiment

The Woburn Organic Manuring experiment managed by Rothamsted Research (Mattingley *et al.* 1973a & b) was started in 1964. It aimed to compare within a single long-term experiment, the treatments to increase soil organic matter, which had previously been tested in separate experiments at Woburn leading up to the 1960s. The experiment continues to this day with modifications and its purpose is to evaluate, from crop yields and soil analyses, the cumulative effects of organic matter on a light, poorly structured, soil with a long history of arable cropping

The experiment to date falls into three distinct stages. In stages (i) and (ii) there was a six-year, fertility build up phase followed by 10 (i) or 8 (ii) years of cropping. Subsequently, after a gap of about eight years the experiment was restarted with a simpler blocking structure and continuous, annual strategy of organic amendment. The experiment followed a similar rotation for the first 10 years, and up until 1990 potatoes were grown. Although the older data (1966-1989) reflect the varieties and management of the time, they do contain yields from 6 potato crops. The original rotation was potatoes-winter wheat-sugar beet-spring barley. In stage (i) two test crops were grown each year each on two of the four blocks. The second stage tested both a winter wheat-potatoes-spring barley sequence as well as 8 years of continuous wheat. The latter is far less typical of today's cropping patterns but is very useful as a resource to evaluate models. The different crops, their sequence and potential residual effect at the end of the sequence add levels of complexity that monoculture avoids. The current rotation is spring barley-winter beans-winter wheat-maize-rye.

During the first build-up phase (1965-72), four rates of N only were applied to crops including a control with zero N. Amounts of N were generally less than during the test phases (1972-1981, 1987-1994) and almost certainly sub-optimal for cereals. However, after correcting for the amounts of N applied with the amendments it is apparent that the cumulative yields on the plots with FYM (81.5 t ha-1 ± 0.25) significantly exceeded the amount produced with mineral fertiliser alone (70.1 ± 0.66 t ha-1). Mattingley *et al.* (1974) confirm that this is so even after controlling for the amount of N added in the FYM. The yield increases on plots receiving straw or peat as an amendment were less (Mattingley *et al*., 1974) but statistically significant. There was no difference between control treatments and those growing a green manure during the build-up phase to increase organic matter in soils.

Beet and Potatoes are reported as fresh weights. Their data are thus approximately half an order of magnitude greater than cereals in the rotation which are reported a dry matter. Besides this, yields vary in response to the weather and to disease each year. In order to control for these different factors and to try to reduce the variability in data to responses to amendment and N fertiliser alone, we divided data by the mean of the controls each year (Fs, Fd) (Table 19). Hijbeek *et al.* (2016) found that yields from spring or root crops such as potatoes were much more likely to benefit from adding organic matter to soils than winter cereals.

Work elsewhere in the Rotations Research Partnership project suggested that potato yield increases in plots amended with organic matter were less apparent in dry weight yields than in fresh matter. Data from our Woburn experiment pointed to sustained yield increases where OM was applied whether the results were reported as fresh or dry matter.

The experiment continues to the present day. However, there was a change to the blocking structure in the yields reported from 2004 and the rotation no longer includes potatoes. No N was applied between 1995 and 2003 and so these results also play no role in the current report.

4.3.1.2. The Fosters experiment at Rothamsted

The experiment on Fosters field to assess the rapidity with which benefits build-up in relation to different rates, and types of OM amendment to crops yields. It started in the autumn of 2012, with the first years' harvests in 2013. It has run continuously since and is in its 9th year at the time of writing with a crop of beans to examine the interaction with amendment and leguminous cropping. Plots receive the same kind and amount of organic amendment each year, N rates, however, rotate.

Funded initially by HGCA, the aim was to demonstrate that the benefits of OM accrue quickly but not immediately (2 years or so) and to examine differences between Farm Yard Manure (FYM), compost (comp), Anaerobic Digestate (AD) and crop residues (straw) at rates of 0 (control), 1, 2.5 and 3.5 t C applied per hectare. During the first four years, two rotations were assessed in separate blocks on the experiment (spring_barley – winter_wheat – winter_oats-spring_barley and winter_wheat – winter_oilseed_rape – spring_barley – winter_wheat) such that a spring cereal and winter cereal were compared both at the start and end of the experiment. A subsequent years' funding from SARIC (NE/M016714/1) was obtained to begin a trial where the expected decline in benefit of OM could be traced. From 2017 the whole experiment was given over to the same crop each year, but whilst two of the blocks continued with the same amendment regime as they had received since the start, amendment ceased on the other two blocks. After two years some additional trials of a P fertiliser (not reported here) took place on part of the experiment. To facilitate this, the different rates of application of carbon were discontinued, but the series which currently and historically received 3.5 t C/ha at 5 different rates of N continued. Crops grown since 2016 are winter_wheat – spring_barley – winter_oats – winter_oil_seed_rape – winter_beans.

4.3.2. Nutrient response curves

To assess the simultaneous response of crops to organic matter and to nitrogen fertiliser a combined response curve is needed. Two separate response curves were tested in the evaluation of yields from experimental plots receiving organic amendments and a range of fertiliser N treatments.

4.3.2.1. Inverse polynomials

Response curves relate crop yields to levels of applied nutrients such as from fertiliser. Here we follow the semi-empirical theory for fertiliser response developed in (Greenwood, 1971). This theory proposes that the relation between yield and nutrient supply can be expressed as an inverse polynomial of the form

(1)

$$\frac{1}{Y(N,\ldots)} = \left[\frac{1}{A} + \frac{1}{B(N_s + N)} + \cdots\right]\left[\frac{1}{1 - (N_s + N)/\alpha}\right]$$

where Y represents yield and N the total amount of applied nitrogen from inorganic fertiliser. The three dots ellipsis refers to possible additional terms related to other nutrients such as phosphorus and potassium, which we disregard in this report. Note however that the developments to follow can be extended easily to these nutrients. The parameters A, B and N_s represent respectively: the theoretical maximum yield obtainable before adverse effects of excess nitrogen take effect (i.e. Y∼Y(N\/N_s≫1)), the maximum crop response rate (i.e. the slope of the response curve for no application B∼Y^' (N=0) and the indigenous soil nitrogen prior to fertiliser application. The parameter α corresponds to a growth inhibitor coefficient associated with the osmotic pressure increase in the root zone determined by the nitrogen level, leading to the response curve downturn commonly observed.

Mechanistically, the parameter B can be related to the mass flow transport of nitrogen within the soil, which establishes a nitrate concentration gradient decreasing away from the root surface (Greenwood *et al*., 1971). As soil organic matter and carbon turnover are key to determining soil structure and its ensuing water flow and nutrient transport properties (Neal *et al*., 2020), this suggests that B may change with the soil carbon content, say C. For simplicity here, we will assume the linear relationship

(2)

$$B = \tilde{B}(C_s + C)$$

where Cs represents the indigenous soil organic carbon. Equations (1) and (2) form the two-dimensional response curve equation that we use throughout this report. Note that here we are neglecting the effect of additional nutrients provided by the organic amendments.

4.3.2.2. Parameter identification

We present and discuss two different methods to fit the six-parameter response curve (1)–(2). We use a set of data from the Woburn Organic Manuring long term experiment when winter wheat was grown. Numerical computations are done with the Matlab nonlinear least squares routine LSQCURVEFIT.

4.3.2.3. ‘Static’ response: direct response to carbon inputs.

This first method of parameter identification assumes that crops respond directly to the application amounts of nitrogen and carbon. Here, our parameter identification methodology is based on averaging crop responses over several years of data so as to smooth out interannual fluctuations, mainly from the variability of weather. In contrast to the second method below, this averaging of yield data over several seasons takes no account of the time evolution of fertility. However, this approach is inconsistent with the optimal control technique that we develop later and should not therefore be considered optimal. However, it gives a good benchmark for the parameter values to expect for response curves of the form (1)–(2).

We use three years of data (2006, 2011, 2016) for winter wheat that we divide into three subsets characterised by their amounts of carbon added annually corresponding to 0, 0.93 and 2.3 t C/ha as farmyard manure (FYM). Out of the whole set of organic amendments, we consider only the F(Fd), DG10 and DG25 type (Table 30). Such datasets can be used to fit the response curve (1)–(2) in different ways: taking either these three sets separately (method 1 in Table 31), or all together (method 2 in Table 31).

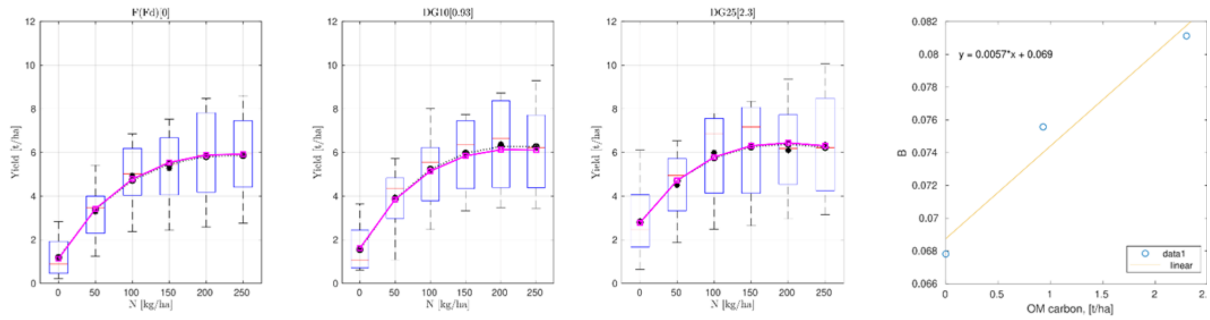
Table 30. Organic Manuring treatments at Woburn

Treatment	Description
Dg	FYM at approximately 3 t C/ha/year
Fd	Mineral nutrients apart from N applied at a rate to be found in an FYM application equivalent to 3 t C/ha/year
Fs	Mineral nutrients apart from N applied at a rate to be found in a Straw application equivalent to 3 t C/ha
Gm	A green manure crop before the spring sown crops in the rotations
Lc	Ley with clover
Ln	Ley with applied nitrogen
Pt	Peat until 1972 at approximately 3 t/ha/year. Ley 1979-1986 and as a subsequent test
St	Wheat straw applied at approximately 2.5 t C/ha

In method 1, the explicit dependence on C from Eq. (2) is disregarded and three sets of parameters can be identified from the subsets. Table 31 shows that the organic matter treatment strongly influences the levels of indigenous nitrogen. A linear relationship exists between the B value and the carbon content (Figure 3). This strongly supports introducing the carbon dependence in the response curve (1) assuming (2). It also allows fitting the data with method 2, which is more parsimonious.

In method 2, we use the whole three subsets of OM treatments at once to determine a single set of parameter values for A, $\tilde{B}$, C_s and α. We allow N_s to depend on the carbon content, however. This approach gives a particularly good result.

Figure 3. ‘Static fitting’ of yield response curves (1)–(2) as described in4.3.2.2. Dataset: Woburn for winter wheat (2006, 2011, 2016). Symbols: (*) mean yield over the four blocks, (black dotted line) parameter fitting for (1) only using the three OM treatments individually (method 1 in Table 31), (magenta solid line) parameter fitting for (1)–(2) (method 2 in Table 31). The boxplots represent the variability within the four blocks in the WOM data for the three years considered here.



4.3.2.4. Dynamic’ response: accounting for the decay of fertility.

The Woburn Organic Manuring long term experiment (section 3.1.1) that has run from the 1960s and until the present day had a useful experimental phase during the 1980s and 1990s where continuous winter wheat was grown. The experiment itself was running before this time and continued afterwards. Between 1981 and 1986 organic material were applied or leys used to build-up organic matter on soil. Following on from this in 1987 by a second phase where no organic matter was applied but a full crop response to several levels of N was evaluated each year until 1994. In this second phase, winter wheat was cultivated under different inorganic fertiliser rates.

Over the eight years of data, yields of winter wheat varied greatly from year to year, almost certainly as a result of the different weather in each year. Van der Pauw (1962) demonstrated the relationship between the loss of N from leaching and reduction in yield in certain crops as a result of winter rainfall, but other factors such as radiation receipt and temperature and development and sowing and disease are also almost certainly responsible for the interannual variability.

However, we found that we could avoid this difficulty by looking at the time variation of the extra yield gained from the organic matter applications. We define the extra yield as the difference between the yield observed from plots which have received some OM treatments in phase 1 and the yield measured from the control plots which have not received any OM amendments. In this way we isolate the change in yield that results from the decline in OM alone. That is

(3)

$$\Delta(\mathrm{N},\mathrm{C_t}) = Y(N,C_t) - Y(N,0)$$

This experiment clearly shows that, during cultivation, the extra yield gained by the OM applications decreases with time (Figure 4(B)). This feature reflects the slow decay of the soil carbon content. Here we discuss a possible method to estimate the carbon decay rate from yield data, as well as determining the parameters of the response curve.

Our identification method splits the data into two components. The first component consists of a subset of data which received no organic matter, averaged over all the years available and distinguishing between six nitrogen doses. The second component corresponds to the extra yield data Δ computed for each year. Here we do not average yield over the years. For each nitrogen treatment, we computed the mean yield over all the plots that received organic matter on the one hand to estimate $Y(N,C_t)$- the yield with applied carbon at each of several N rates. On the other hand, to estimate $Y(N,0)$, the yield without applied carbon, we computed the mean yield over all the other plots which did not have organic inputs. Figure 4 presents these two datasets.

The novelty in this methodology is to consider the time evolution of the soil carbon content which yield responds to. This is not necessarily the whole carbon content of the soil, but a component that is active in some way relevant to yield. This component may help determine the water-holding capacity for soil or the hydraulic conductivity, for example. For simplicity, we assume that carbon decays linearly according to the simple homogenous recurrence equation

(4)

$$C_t = \kappa\, C_{t-1},$$

where the decay constant $\kappa \le 1$ represents the proportion of carbon remaining in season t from the previous season. Note that this proportion also gives the characteristic timescale of this process, which can be estimated from the half-life period defined as $t_{1/2}=\ln(1/2)/\ln(\kappa)$

(the decay constant κ introduced here is connected to the continuous decay rate k_c in 4.3.2.5 by $k_c \equiv -\ln(\kappa)$).

At Woburn, winter wheat was grown each year from 1987 (although on alternating blocks until 1990), while organic matter amendments were stopped in 1986. As a result, according to (4) we expect carbon to decay as

(5)

$$C_t = C_{86}\kappa^{t-1986},$$

C_{86} being the level carbon stored following the first phase of the experiment.

We substitute this expression into (Eq.3) to fit the extra yield data in combination with 'zero carbon' yield data and identify at once the response curve parameters $p=(A,\tilde{B},N_s,C_s,\alpha)$ together with the values C_{86} and κ. This is easily performed from defining the vector-valued function

(6)

$$F(p,\kappa,C_{86},N,t) = \begin{pmatrix} Y(p,N,0) \\ \Delta(p,N,C_{86}\kappa^{t-1986}) \end{pmatrix},$$

which is used with the Matlab routine LSQCURVEFIT.

The results of fitting the inverse polynomial response curves are presented in Table 3.2.2.1. Regarding the carbon dynamics, we found

$\kappa=0.686, C_{86}=8.561\ \text{tC/ha.}$

The value of κ gives $t_{1/2}=1.839$ years. A word of caution. Note that some of the nitrogen rates led to negative values for the extra yield in the years 1992 and 1993. Given that the data are variable to within one tonne or so, some results are very likely to be negative if on average the expected value is zero.

Despite this, we think that the identification method presented in this section has the great advantage to allow the determination of a single set of parameters for the response curve. Most importantly, this method also paves the way for integrating the carbon dynamics into the picture.

Figure 4. 'Dynamic fitting': example of decay of the extra yield following the discontinuation of organic amendments. Dataset: Woburn (period: 1987–1994). (a) LH panel: average yield response, (b) RH panel additional yield on each plot receiving the rates of N stated in the legend.

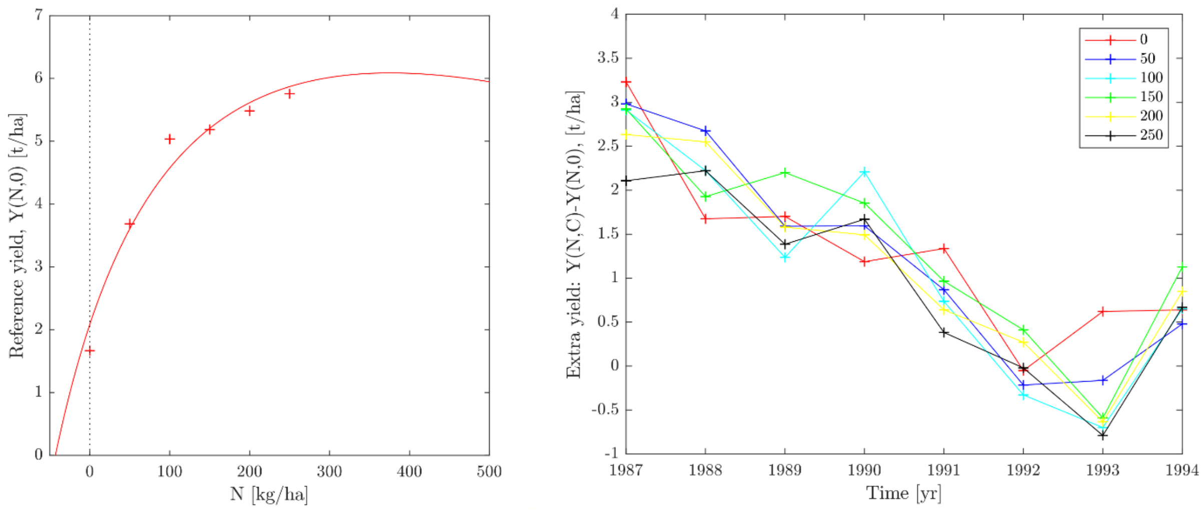


Table 31. Parameter identification for the inverse polynomial response curve (1)–(2) using the Woburn organic manuring long term experiment. See Figure 3 and Figure 4.

Fitting method	Dataset	A	$\tilde{B}$ (B for (1))	N_s	C_s	α
(1) 'Static' (Individual)	F(Fd) [0]	18.549	0.067817	19.171	∅	741.19
	DG10 [0.93]	19.419	0.075575	23.058	∅	730.18
	DG25 [2.3]	18.663	0.081131	43.645	∅	726.08
(2) 'Static' (whole)	F(Fd) [0]	18.891	0.0052492	17.861	13.211	728.7
	DG10 [0.93]	18.891	0.0052492	24.591	13.211	728.7
	DG25 [2.3]	18.891	0.0052492	43.021	13.211	728.7
(3) 'Dynamic'	[0] + extra yield	11.668	0.0240	43.048	2.527	1751.4

4.3.2.5. Linear plus exponential models

The second formulation of the response of crop yield to both nitrogen and organic amendment (carbon) builds on the linear plus exponential function widely used in the evaluation of yield responses to nitrogen fertiliser in the trials that support the development of the fertiliser guidance manual (RB209 AHDB). The extension of this function to organic amendment or other nutrients is less structured than for the reciprocal curve, but the parameters may be more familiar to scientists currently working in the field. The familiar *lexp* model is:

(7)

$$Y = a + br^N + cN$$

Where Y is the yield and a (>0), b (<0), r (~0.99) and c (<0) are parameters. This equation can be written

$$Y = a\left(1 - r^{N+b^{/}}\right) + cN$$

Where $r^{b/}$ equals b/a. Extending this for organic matter and using C to represent the organic matter accumulated in soil

(8)

$$\mathrm{Y} = \mathrm{a}\left(\left(1 - {r_1}^{N+b^{/}}{r_2}^{Cs+\mathrm{C}}\right) + b_1(1 - {r_2}^{C})\right) + \mathrm{c}_1 N + \mathrm{c}_2 C.$$

Where a and $b^{/}$ are constants as before, r_1 and r_2 are parameters with values in the range 0-1 with the expectation that each will be ~ 0.99, c_1 and c_2 have values < 0, Cs is a parameter that corresponds to the yield-enhancing power of the unamended soil and b_2*a is the maximum increase in yield that can be brought about by amending soil.

The amount of carbon, C, or rather yield-enhancing capacity in soil as a result of adding organic matter can be modelled either as a recurrence or as a differential equation. Adopting the former for consistency with what follows:

$$C(t) = k_c C(t-1) + A, t \le \tau, \ \text{ or } \ C(t) = k_c C(t-1), t > \tau.$$

Where A is the amount of annual amendment during the first τ years and k_c is a rate constant. This has solution:

(9)

$$C(t) = \frac{A}{1-k_c} - {k_c}^t\left(C_s - \frac{A}{1-k_c}\right), t \le \tau, \quad \text{or} \quad C(t) = C(\tau)k_c^{t-\tau}, t > \tau.$$

Or in differential formulation and, where $C(0) = C_s$,

$$\frac{dC(t)}{dt} = -\mathrm{k_c}\mathrm{C}(t) + \mathrm{A},\ \mathrm{t} \le \tau, \qquad \text{or} \qquad \frac{dC(t)}{dt} = -k_c C(t), t > \tau,$$

with solution

(10)

$$C(t) = \frac{A}{k_c} + e^{-k_c t}\left(C_s - \frac{A}{k_c}\right), t \le \tau, \qquad \text{or} \qquad C(t) = C_\tau e^{-k_c(t-\tau)}, t > \tau.$$

4.3.2.6. Curve fitting

Parameters in Eqs. (7) and (8) above were fitted to data from the Woburn Organic Manuring experiment and from Fosters field using a Genetic Algorithm (Charbonneau and Knapp, 2004) to search the entire parameter space for a global solution and thereafter using a simplex (Press *et al*., 2007) to home in. Because the simplex tended to lodge on a local solution despite the initial global search, an iterative annealing technique was used to sequentially improve on each of several simplex solutions in turn.

4.3.3. Static analysis using the reciprocal response curve

4.3.3.1. One-dimensional analysis along nitrogen

It is quite natural to identify the response curve as a production function whose output is the yield Y as a function of the inorganic nitrogen input N due to fertiliser applications. Denoting p and c the price of the crop and the cost of inorganic fertiliser respectively, the profit is defined by the nonlinear function

(11)

$$J(N) = pY(N) - cN.$$

Without any additional constraint to satisfy, the optimum nitrogen input N_o maximising the profit corresponds to a critical point of $J(N)$, which solves $J'(N_o) = 0$ by definition. The derivative of a function is denoted with a prime. Therefore, the unconstrained maximisation of profit leads directly to the BER (Break-Even Ratio) condition

(12)

$$Y'(N_o) = c/p,$$

giving the optimum rate of fertiliser application to obtain maximum economic yield. Note that we can define the metric

(13)

$$\gamma(N) = pY'(N) - c$$

which characterises a distance to optimality. As long as $\gamma > 0$, the BER condition is not met, and profit could be increased by adding more nitrogen until $\gamma = 0$. Such a quantity is usually interpreted as a shadow price in economics. If we denote δN an increment of nitrogen fertiliser, this price multiplied by δN represents exactly the increment in profit δJ gained from the ensuing increase in yield $\delta Y = Y'\delta N$, i.e.

(14)

$$\gamma\delta N = pY'(N)\delta N - c\delta N \;=\; p\delta Y - c\delta N \;=\; \delta J.$$

This is nothing but formalising mathematically the intuitive reasoning behind the BER approach. If $\gamma < 0$, the value of the extra yield obtained is less than the cost of the extra N to grow it; money is being wasted and so profit declines.

4.3.3.2. Two-dimensional analysis along nitrogen and carbon

The static optimisation of fertiliser application can be generalised to more than one nutrient. Expression (11) remains valid but needs to be interpreted as a function of several variables. Although organic matter is not directly a plant nutrient, a yield response curve can still be deduced in which yield depends on the carbon content (or amount applied) using inverse polynomials as showed in the previous section.

To be explicit, the two-dimensional interpretation of (4) reads.

(15)

$$J(N, C) = pY(N, C) - cN - qC,$$

where q is the cost of applying organic matter. The unconstrained optimum rates (N_o, C_o) of inorganic nitrogen and carbon from organic matter amendments then correspond to the critical point of $J(N, C)$ now solving the system

(16)

$$Y_N(N, C) = c/p, \qquad Y_C(N, C) = q/p,$$

where we denote $Y_N = \partial Y/\partial N$ and $Y_C = \partial Y/\partial C$ the partial derivatives of Y with respect to N and C. We interpret this system of two equations as the two-dimensional BER condition. As in the one-dimensional case, we can define the nitrogen and carbon shadow prices

(17)

$$\gamma(\mathrm{N}, \mathrm{c}) = pY_N(N, C) - c, \eta(\mathrm{N}, \mathrm{C}) = pY_C(N, C) - q.$$

4.3.4. Dynamic analysis

Here we aim at computing the optimal application rates of inorganic nitrogen and organic matter to apply every year over a cultivation period of *T* years, in order to maximise the overall profit. We follow a nonlinear programming approach to solve the discrete-time optimal control problem defined below.

4.3.4.1. Formulation

Our formulation relies on the key assumption according to which both the soil nitrogen and carbon evolve in time season after season. Importantly this implies that we need to distinguish the nitrogen and carbon content in the soil, N_t and C_t say, from the nitrogen and carbon content in the inputs, U_t and V_t say. Note that this distinction is irrelevant in the static analyses developed above. In terms of optimal control, the former set of variables correspond to *state variables*, while the latter set of variables represents *control variables*.

In this report, we will assume that crops respond to the state rather than control variables, because the former characterise the soil. In contrast to the static approach, the dynamics between state and control variables must also be considered. Modelling the processes governing the (spatio)temporal evolution of the soil nitrogen and carbon is fraught with difficulties and is still a matter of intense research. For the problem at hand, however, some useful insights can be gained from treating this multitude of complex processes as simple recurrence equations.

We will suppose that the dynamics of the soil nitrogen and carbon is linear and uncoupled and that their respective concentrations in season t result from the sum of a carry-over proportion from the previous season $t - 1$ with the actual nitrogen input and organic matter amendment in season t, $t \in [\![1, T]\!]$. Mathematically this translates into the two recurrence equations

(18)

$$N_t = kN_{t-1} + U_t, C_t = \kappa C_{t-1} + V_t.$$

They can be integrated once initial conditions describing the level of pre-existing fertility conditions at $t = 0$

(19)

$$N_0 = N_i, C_0 = C_i,$$

and a sequence of inputs (U_t, V_t) are known.

The optimal control theory is a mathematical optimisation technique which determines the optimal temporal trajectories (sequence) for the control variables to maximise (or minimise) some *objective function*, J say, subject to a set of constraints such as the two recurrence equations above. Here we seek to maximise profit over a finite period of T years, our objective function being

(20)

$$\mathrm{J}(N_t, C_t; U_t, V_t) = \sum_{t=1}^{T} [\, pY(N_t, C_t) - cU_t - qV_t].$$

In contrast to the static analysis developed above, we now deal with a discrete-time dynamical system corresponding to a deterministic multistage decision process (Bellman, 2013; Sage and White, 1977, Sethi, 2019). The time dependence involved by the recurrence equations needs a specific treatment that we explain now.

4.3.4.2. Necessary conditions for optimality

The presence of (time-dependent) constraints in optimisation problems such as Eq. (11) requires variables, called Lagrange multipliers, equal in number to the number of constraints. The Lagrange multipliers ensure that the constraints are always satisfied. In broad terms, these multipliers estimate how much the objective function changes due to a unit change in the value of a constraint. That is, in our case, a change in the increment of fertility $N_t - N_{t-1}$ and $C_t - C_{t-1}$.These multipliers generalise the BER concept in the sense that they reflect the change in profit that results from a unit increment of the soil fertility. By fertility, we mean the combined effect of both the fertiliser and organic matter applications together with the internal dynamics (gain or loss) of the nitrogen and carbon in the soil**.** In economic terms, these multipliers are shadow prices giving a monetary value to the increase (or loss) of fertility. Our analysis thus generalises the BER concept to all aspects of fertility (if the yield response is well-understood) (i) in the current year and (ii) future years (in terms of today's outlook) and for (iii) for multiple inputs.

In contrast to the unconstrained static optimisation that we presented in Section 4.3.3, it is not simply the objective function that needs to be differentiated with respect to the variables but the so-called LaGrangian function, L say. Such a function is defined as a linear combination of the objective function and the constraints, which reads in our case

(21)

$$\mathrm{L} = \sum_{\mathrm{t}=1}^{\mathrm{T}} \left[[\mathrm{pY}(\mathrm{N_t}, \mathrm{C_t}) - \mathrm{cU_t} - \mathrm{qV_t}] + \lambda_t(kN_{t-1} + U_t - N_t) + \mu_t(\kappa C_{t-1} + V_t - C_t) \right]$$

$$+\lambda_0(N_i - N_0) + \mu_0(C_i - C_0) + \sum_{t=0}^{T}(\nu_t N_t + \upsilon_t C_t) + \sum_{t=1}^{\mathrm{T}}(\zeta_t U_t + \xi_t V_t).$$

We denote λ_t and μ_t the Lagrange multipliers associated with the two recurrence equations governing the dynamics of nitrogen and carbon respectively (the multipliers associated with the initial conditions are denoted λ_0 and μ_0). The variables $\nu_t, \upsilon_t, \zeta_t, \xi_t$ are Lagrange multipliers needed to ensure that N_t, C_t, U_t, V_t are all non-negative quantities. We will see later that ξ_t becomes key to the analysis once organic amendments stop. Note that all these multipliers are time dependent necessarily. Hence, one of the first tasks is to determine their equations of evolution. This is object of optimal control theory.

Without entering into the mathematical details, taking the partial derivatives with respect to the state variables (the soil N and C) leads to the recurrence equations that we are seeking,

(22)

$$\mathrm{k}\lambda_{t+1} = \lambda_t - pY_N(N_t, C_t) - \nu_t, \quad \kappa\mu_{t+1} = \mu_t - \mathrm{pY_C}(N_t, C_t) - \upsilon_t.$$

A similar calculation at the initial and terminal times, T, gives the associated boundary conditions

(23)

$$\lambda_T = \mathrm{pY_N}(N_T, C_T) + \nu_t, \mu_T = \mathrm{p}Y_C(N_T, C_T) + \upsilon_T,$$

and

(24)

$$\lambda_0 - \nu_0 = k\lambda_1, \mu_0 - \upsilon_0 = \kappa\mu_1.$$

The derivatives with respect to the control variables (i.e. the inputs) yield two important relations, namely

(25)

$$\lambda_t = c - \zeta_t, \mu_t = q - \xi_t.$$

Finally, we have the complementary slackness conditions

(26)

$$\nu_t \geq 0,\ \nu_t N_t = 0; \quad \upsilon_t \geq 0,\ \upsilon_t C_t = 0; \quad \zeta_t \geq 0,\ \zeta_t U_t = 0; \quad \xi_t \geq 0,\ \xi_t V_t = 0,$$

which close the system of equations governing the optimal trajectory that one must follow to maximise profit over T seasons. For each season t, note that these conditions imply that the additional Lagrange multipliers $\nu_t, \upsilon_t, \zeta_t, \xi_t$ are all zero as long as the state and control variables are positive. In the next section, we will see that this is important as this shows that λ_t and μ_t are constants equal to the costs of fertiliser and organic matter amendments as long as they are non-zero.

We remark that it is a specificity of the optimal control theory to show that optimal trajectories are not only determined by the initial conditions but also by a set of terminal conditions. This leads to a so-called two-point boundary value problem. For discrete-time problem it is however more effective to turn this around by reformulating this approach in terms of nonlinear programming. It makes the numerical solution of the above equations also more amenable in practice.

4.3.5. Computation of an optimal trajectory

The optimal trajectory leading to optimal inputs maximising profit solves the nonlinear dynamical system formed by the recurrence equations (11) and (15) associated with the boundary conditions (12) and (16), subjected to the additional conditions (17)–(19).

This nonlinear system has the steady-state (N_*, C_*, U_*, V_*), which is obtained from solving

(27)

$$(1-k)c = pY_N(N_*, C_*), \qquad (1-\kappa)q = pY_C(N_*, C_*).$$

We call this the dynamic BER equilibrium. The associated values of the inputs follow from the equilibrium solution of (11)

(28)

$$U_* = (1-k)N_*, \quad V_* = (1-\kappa)C_*.$$

Because we allow fertility to build up with time, these two equations show that the nitrogen and carbon inputs each year can be reduced, compared to what would be expected from the static BER analysis. Note that the steady-state (N_*, C_*, U_*, V_*) represents the optimal control solution of our problem for the infinite horizon case $T \to \infty$.

We emphasise that these formulae are reminiscent of equations (16) from the two-dimensional static analysis in Section 4.3.3.2 but clearly modified by the decay constants. This is not a surprise as the dynamics of nonlinear dynamical systems tend to be controlled by attractors such as equilibria. In the numerical results presented later, we will see that this steady-state is very important as it governs the levels of soil fertility and inputs along any optimal trajectory until a critical season at $t=t_*$ years from which time organic amendments must be reduced and then stopped if maximum profit is to be obtained.

Note finally that this steady-state is characterised by Lagrange multipliers whose values are set by the cost of inputs, i.e. $(\lambda_*, \mu_*) = (c, q)$. Here we see a clear example of the interpretation given to the Lagrange multipliers as shadow prices. Once the steady-state is reached, they must equal the cost of the inputs, as is the case with the classical BER concept for nitrogen.

For the full computation of an optimal trajectory, as we hinted in the previous section, we found that it is numerically much easier to reformulate our discrete-time optimisation problem as the search of a constrained minimum of a function of several variables as is done in nonlinear programming (Mangasarian, 1969; Sage and White, 1977). The trick is simply to minimise $-J$ defined as a scalar function of an unknown vector whose components are made of the state and control variables of every season. Numerical solution is then easily obtained from using an optimisation routine such as the Matlab FMINCON routine.

4.4. Results

4.4.1. Optimal trajectories and input rates

Unless otherwise stated, the numerical results presented in Section 4.4.1 are performed with the reciprocal response curve (Eqs. 1-2) whose parameters (Table 31) are identified with the methodology described in 4.3.2.2. We recall that the rate of loss of yield enhancement due to organic amendments is $\kappa = 0.686$ in this instance. We set the decay rate of nitrogen arbitrarily to $k = 0.15$ ($t_{1/2} = 0.37$ yr), mimicking the observed rapid loss of mobile nitrogen.

According to (Ref Farm Management Handbook 2020, & Piras personal communication) we use typical orders of magnitude for the crop price, the cost of nitrogen and organic matter set to $p = 100$ £/ha, $c = 1$ £/ha, $q = 80$ £/ha. Note that the profit functions (Eqs. 11, 15) can be normalised with respect to the crop price p. In turn all our numerical calculations remain valid for costs of inputs such that $c/p = 0.01$ t/kgN and $q/p = 0.8$ t/tC.

4.4.1.1. Static analysis

Figure 5 illustrates the calculations and concepts presented in Section 4.3.3.

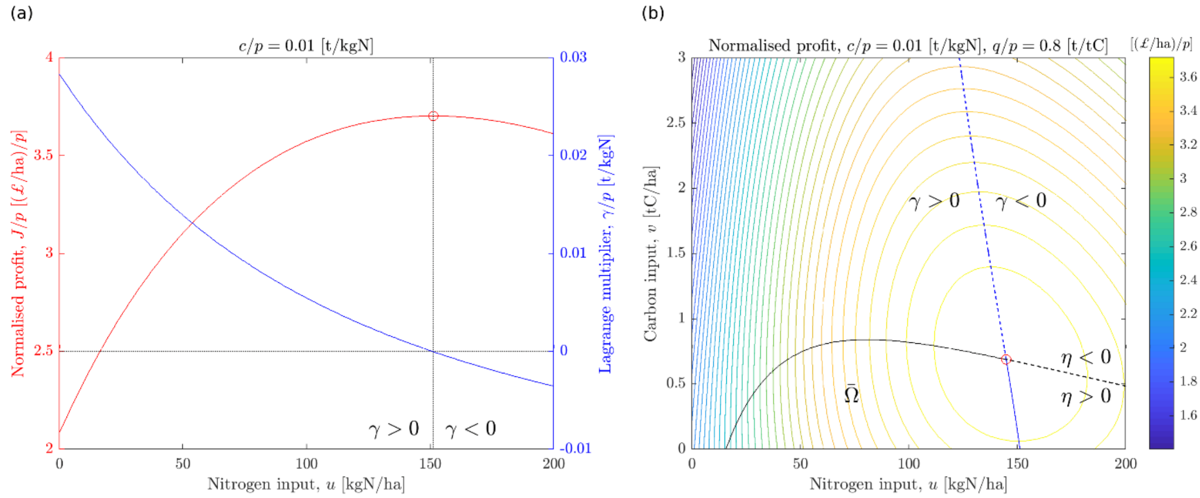
In the one-dimensional case (Section 4.3.3.1), solving Eq. (12) for the parameter values listed above (Table 31) yields the BER nitrogen rate $N_o = 151$ kg N/ha. The corresponding maximum of profit is $J = 370$ £/ha. In Figure 5(a), the locus of the one-dimensional BER optimum is highlighted with a red circle symbol. We point out that this N_o rate corresponds, by definition, to the rate at which the 1D nitrogen shadow price γ cancels out. A decreasing shadow price γ (blue curve) for the domain of profitability $N < N_o$, a, is of course associated with increasing portion profit (red curve).

These features readily translate to the two-dimensional case (Section 4.3.3.2). The landscape of profit is still concave but now looks like a hill with a relatively flat summit located at the 2D BER rates $N_o = 145$ kN/ha and $C_o = 0.69$ tC/ha; $J(N_o, C_o) = 378$ £/ha. In Figure 5(B), we use an iso-contour plot to show the variation in profit with changing nitrogen and carbon inputs. Such a landscape is structured around the two curves defined implicitly by expressions (17). The first curve (blue) is designated as the N-line where $\gamma(\mathrm{N}, \mathrm{C}) = 0$; the second curve (black) as the C-line where $\eta(N, C) = 0$. They intersect at the two-dimensional BER point (red circle). As in the one-dimensional case, only a limited domain of the (N, C)-input plane is profitable in the sense that an increase in the input rates can generate more profit. This is the domain $\overline{\Omega}$ in Figure 5(b) in which both the shadow prices γ and η are non-negative. Outside this region, applying fertiliser and organic matter becomes too costly with respect to the ensuing yield increase.

Note that, if one were limited in the amount of organic amendment, the optimum rates would be given by the solid blue line (Figure 5(b)). If one were limited in terms of nitrogen, the solid black line would give the optimum rates to apply.

This analysis combining nitrogen and organic matter clearly shows that nitrogen rates can be reduced thanks to organic amendments (blue line Figure 5(b)). In the static analysis, this shift is modest. The gains in profit are also not very significant. We will see in Section 4.4.1.2 that these conclusions are misleading because the dynamics of nitrogen and carbon has been disregarded.

Figure 5. (a) One-dimensional static profit analysis. Left hand axis and red line plot the increase in profit expected with applied N (lower horizontal axis). Right hand axis and blue line display the change in Lagrange multiplier with normalised cost: price ratio (top horizontal axis) and (b) two-dimensional static profit maximisation. Axes plot rate of carbon applied (v, vertical axis) against amount of N applied (u, horizontal axis). Lines give the rates of C and N applied that are consistent with optimum rate of application of C (black) or N (blue), see Eq. (17). This divides the plotted area into 4 sections. It is only where both Lagrange multipliers $(\gamma, \eta) > 0$ that it is profitable to increase applications (region $\bar{\Omega}$).



4.4.1.2. Dynamic analysis

4.4.1.2.1. Description of typical optimal trajectories

We present two typical optimal trajectories computed for a same cultivation period of $T = 10$ years, but which differ from their initial yield-enhancing carbon content C_0. In both cases, we take the initial nitrogen $N_0 = 0$ to consider the extreme but reasonably realistic case of degraded soil depleted in nutrients, since even fertile soils may lose much N during a winter and before applications of fertiliser in spring.

We start with the worst-case scenario where $N_0 = C_0 = 0$, Figure 6. Because of these initial conditions, the trajectory starts at

$$(N_1, C_1, U_1, V_1) = (N_*, C_*, N_*, C_*).$$

Interestingly, we see that the initial depletion can be compensated by the second season if we provide the soil with inputs equal to the dynamic equilibrium (N_*, C_*) defined by Eq. (27). From year two already, the nitrogen inputs and organic amendments can then drop to their equilibrium values (U_*, V_*). In turn the soil nitrogen and carbon remain at their dynamic BER values until reaching year $t_* = 7$. Figure 7 presents a generic and schematic schedule for organic matter applications under the optimal control theory developed in Section 4.3.4.

For the case with a higher level of initial yield enhancing carbon $C_0 = 10$ t C/ha (Figure 8), the nitrogen behaves in a similar way because the initial level of nitrogen is the same in both cases. This results from our formulation in which the recurrence equations for the dynamics of nitrogen and carbon are uncoupled. However, the behaviour for carbon is very different initially. Because C_0 is large $(C_0 > C_*)$, the optimal trajectory requires a gradual input of carbon over 3 years, starting from none. From the third year, $U_t = U_*$. This initial behaviour is a direct consequence of the slow decay of the active carbon, reminiscent of the Woburn data we have described in 4.3.2.2.

After a short period, dependent on the initial conditions, the optimal trajectory tends to the equilibrium point of our system, Eqs. (27-28). Figure 9 shows the two optimal trajectories described above in the (N,C)-phase plane and how they organise around this dynamic equilibrium point. This dynamic equilibrium is characterised by the soil nitrogen and carbon levels and associated dynamic BER rates $N_* = 114$ kg N/ha, $C_* = 5.82$ t C/ha, $U_* = 96.8$ kN/ha, $V_* = 1.83$ t C/ha for these two examples. Note that these values contrast strongly with those calculated under the static two-dimensional analysis ($N_o = 145$ kg N/ha, $C_o = 0.69$ t C/ha).

Over the 10-year period, we find that the average nitrogen and carbon inputs for these two optimal trajectories are similar with $\bar{U} = 102$ kg N/ha and $\bar{V} = 1.76$ t C/ha (resp. with $\bar{U} = 102$ kg N/ha and $\bar{V} = 1.11$ t C/ha) in the first (resp. second) case. Adding organic matter following optimal trajectories can then lead to both a significant reduction in nitrogen inputs of about 30% and an increase in (average annual) profit of about 25-30% compared to the BER recommendation used in nitrogen fertiliser guidance. This conclusion differs sharply from that in the static analysis case (Section 4.4.1.1).

These two examples clearly show that the dynamics of the optimal trajectory may differ initially depending on the state of the soil prior to cultivation. But both tend to the dynamic equilibrium of the system very quickly. Hence the memory of the soil initial state is rapidly forgotten once the dynamic equilibrium is reached (in our simple description). As a result, the optimal trajectories evolve identically in time during the final years: here for the final $T - t_* = 3$ years. From the eighth season, we see that the nitrogen inputs increase to partly compensate, whilst the organic amendments decrease, reaching zero for the final two years. Figure 8 synthesises the inputs and soil dynamics within the (nitrogen, carbon) phase plane. Note how the nitrogen and carbon input scheduling each year differs quantitatively from the two-dimensional static strategy (the red circle symbol corresponds to the two-dimensional BER rates). This difference results from the slow time evolution governed by the carbon dynamics introduced by the recurrence equation Eq. (18) and controlled by the decay constant κ. (Mathematically, note that the two-dimensional static BER rates correspond to the limit of the decay rates $k, \kappa \to 0$, i.e. a very fast dynamics Eq. (18) in which none (or almost none if $k, \kappa \ll 1$), of the nitrogen and carbon is inherited from one season to the next. What drives yield is only the inputs in this case, fertility does not increase with time in this limit; dynamical effects are switched off.)

We can understand the organic matter application schedule from the dynamics of the Lagrange multiplier μ_t determined by Eq. (22), which we prefer to write here as

$$-(\mu_{t+1} - \mu_t) = pY_C(N_t, C_t) - (1 - \kappa)\mu_{t+1}.$$

Compared to Eq. (17) $\eta = pY_C(N, C) - q$ whose sign indicates when organic matter should be applied (>0) or not (<0) in the two-dimensional static analysis, we recognise in the difference in the right-hand side of this equation an effective dynamic BER for organic application associated with an effective cost $(1 - \kappa)\mu_{t+1}$. This cost would be $(1 - \kappa)q$ in dynamic equilibrium where $\mu_t \equiv q$.

When an optimal trajectory is followed, the equation above must be always satisfied, as well at the end boundary conditions Eq. (23). This means that the level of organic matter amendment must be adjusted to avoid wastage. One can see the dynamics of an optimal trajectory as a sequence of quasi-static two-dimensional BER as we have described in Section 4.4.1.1. However, the numerical values of inputs must be adapted to their equilibrium values governed by Eq. (27) in Section 4.3.5 and the decay constants involved in the recurrence equations (18).

Note finally that, when organic matter amendments stop, a drop in yield is observed. We then attribute the increase in nitrogen inputs over the 3 final years as a way to compensate this yield loss, which would be more pronounced otherwise.

4.4.1.2.2. Effects of the cultivation period, organic matter price and decay constant $(\boldsymbol{T}, \boldsymbol{q}, \boldsymbol{\kappa})$

Numerical simulations for different T and q showed that the time to discontinue organic amendments is two years before the end of the cultivation period and that is a general feature for a wide range of organic matter application prices, Figure 10. For the parameter values in Table 31, we found

$$25 \leq q \leq 130 \text{ [£/tC]}.$$

When organic amendments are expensive $q > 130$ £/t C applications must be stopped one year sooner. Conversely if amendments are cheap (< £25 t C/ha) they can be applied one more year. Given a likely cultivation period of 5-10 years and the current range of price of organic matter applications, we can take the stop time for organic applications as the final two years $T - 1$ and T as a rather general rule given the κ value identified from the Woburn dataset.

Our numerical calculations also show that the rate of organic matter application in the third year before last must be reduced, i.e. $0 \leq V_{T-2}$. This result, combined with the carbon recurrence equation (18.2) with $V_{T-1} = V_T = 0$, implies that the final season yield-enhancing carbon level C_T cannot exceed a given proportion of its dynamic BER equilibrium counterpart C_* set by the decay rate κ, as defined in Section 4.3.5, Eqs (27)-(28). Calculation shows that we have

$$\kappa^3 \leq C_T/C_* \leq \kappa^2.$$

It should not be a surprise as this arises from the geometric (exponential) decay ensured by (18.2). Note that this result generalises easily to

$$\kappa^n \leq C_T/C_* \leq \kappa^{n-1},$$

where $n - 1$ is the number of seasons with no organic matter application, $n = T - t_*$.

Numerically, for the decay rates of the yield-enhancing carbon that we expect, say $\kappa \sim 0.7$, the terminal fertility due to organic matter amendments is then bounded according to

$$30\% \leq C_T/C_* \leq 50\%.$$

This is a rather stark condition, which states that fertility cannot be maintained for more than one year beyond half of what could be accumulated from amendments as a result of the internal dynamics of soil carbon combined with the economics of this problem, both governing the dynamic equilibrium of carbon C_* determined in Section 4.3.5 by Eq. (27). For the range of carbon decay constants κ most probably encountered in soils, numerical simulation shows that $C_T/C_* \leq 40\%$ overall (Figure 18 in Supplementary Information).

Figure 11 presents the effect of the carbon decay constant κ (expressed at the half-life characteristic time $t_{1/2}$) on the organic amendment discontinuation time t_*, averaged total profit, mean and initial nitrogen and carbon inputs. These calculations are done for $q = 80$ £/tC and the reciprocal response curve identified earlier. The organic amendments discontinuation-time is a decreasing stepwise function of the carbon half-life (or decay constant) over a wide range comprising values between about $t_{1/2}^{\min} = 7$ months to $t_{1/2}^{\max} = 7$ years ($\kappa_{\min} = 0.34, \kappa_{\max} = 0.91$). As the active carbon loss slows down (κ rises), the need to replenish the soil with organic matter declines because the losses from one season to the next diminish. As the term κC_{t-1} in Eq. (18) is larger, more carbon remains in the soil the following season (see Figure 16 in Supplementary Information). If the half-life of carbon is more than 7 years, $t_* = 0$ and organic matter applications must then be concentrated in the first year only (see Figure 17 in Supplementary Information). With this reduction in the number of OM applications, we see that the mean level of carbon input $\bar{V}$ is a bell-shaped function of $t_{1/2}$ with a maximum reached about $t_{1/2} = 4$ years, while the mean level of nitrogen input $\bar{U}$ diminishes monotonically. Similar trends are observed for the first year inputs providing the dynamics has half-live below $t_{1/2}^{\max}$. All in all this concurs with a significant increase in the total profit as long as the speed of the carbon kinetics is reduced. Further comments and illustrations are available in Section 4.8.1 in the Supplementary Information of this section.

Figure 6. (a) Nitrogen and (b) carbon optimal trajectory for $C_0 = 0$ tC/ha. The time schedule for nitrogen and carbon amendments divides into three successive portions. First, the inputs in season 1 $(N_1, C_1) = (N_*, C_*)$ compensate for the initial depleted fertility so that the second phase corresponds to the dynamic BER equilibrium. The third and final phase is associated with the reduction and arrest of organic amendments over three years. This discontinuation in carbon inputs is associated with a slight decrease in yield; however, profit is still maximised over T years of cultivation. Parameter values: $T = 10, q = 80, c = 1, p = 100, k = 0.15, \kappa = 0.686, N_0 = C_0 = 0$.

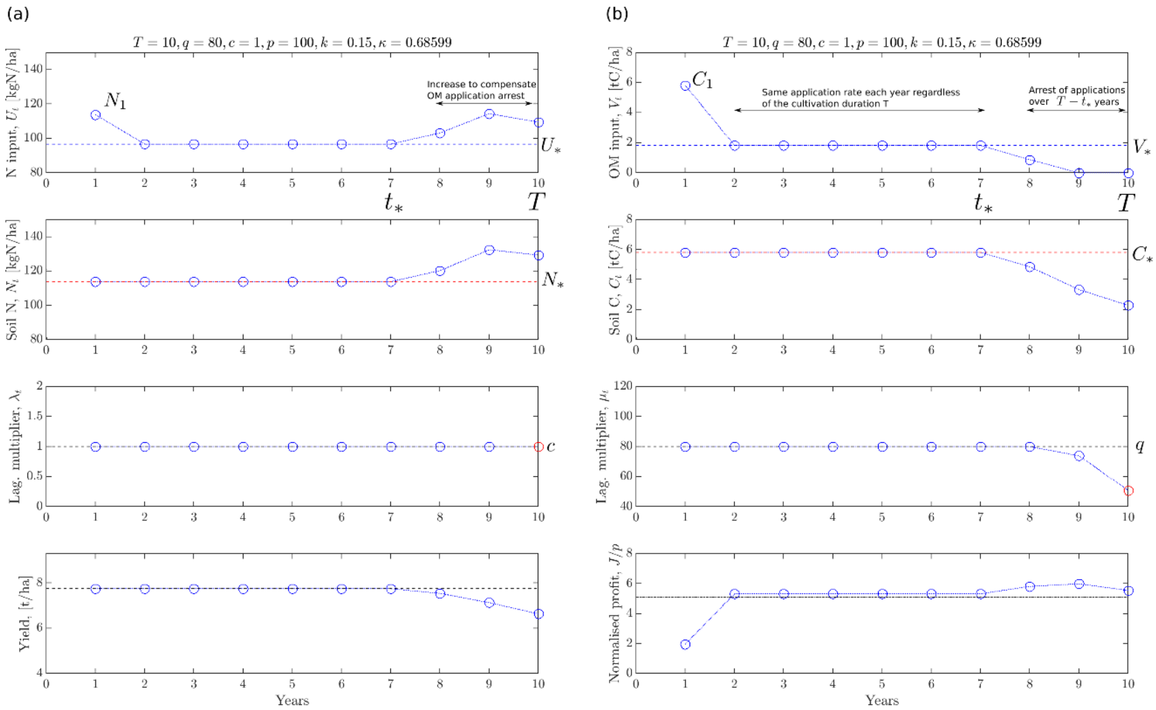


Figure 7. Typical optimal organic matter amendments schedule. Over a cultivation period of T years, organic matter amendments follow a three-step timetable. After an initial input in year 1 whose level depends on the concentration of active carbon C_0 prior to the start of the cultivation period, organic matter is applied at a constant dynamic BER rate V_* (i.e. see dynamic equilibrium Eqs. (27-28)) for $t_* - 1$ consecutive years. Applications are then reduced and stopped over a final phase of $T - t_*$ years.

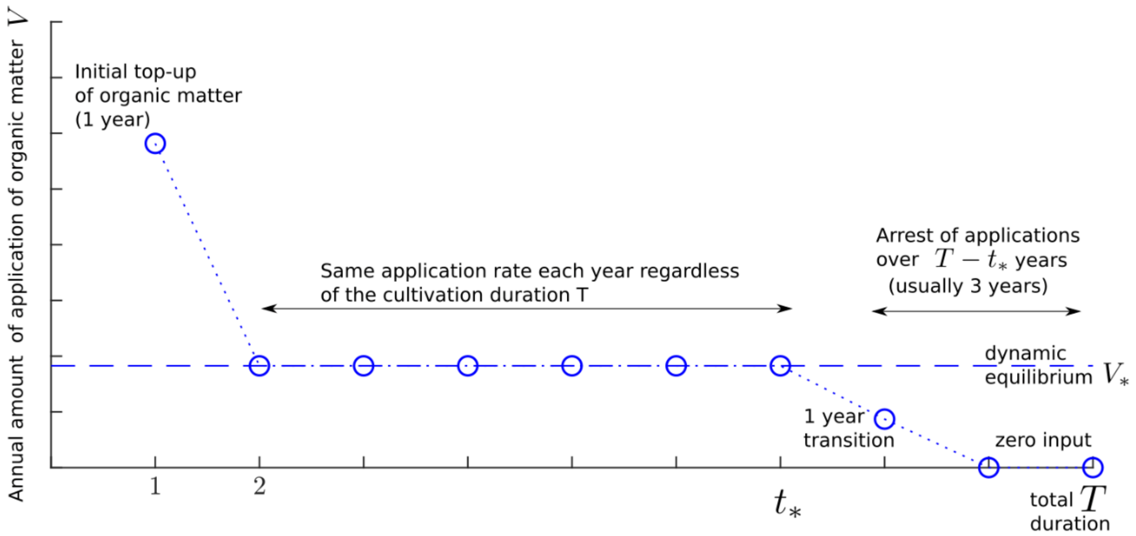


Figure 8. (a) Nitrogen and (b) carbon optimal trajectory for $C_0 = 10$ t C/ha. In contrast with Figure 6, the initial high level of yield enhancing carbon allows a gradual input of carbon over the first three years. The rest of the optimal trajectory is like Figure 6. Parameter values: $T = 10, q = 80, c = 1, p = 100, k = 0.15, \kappa = 0.686$.

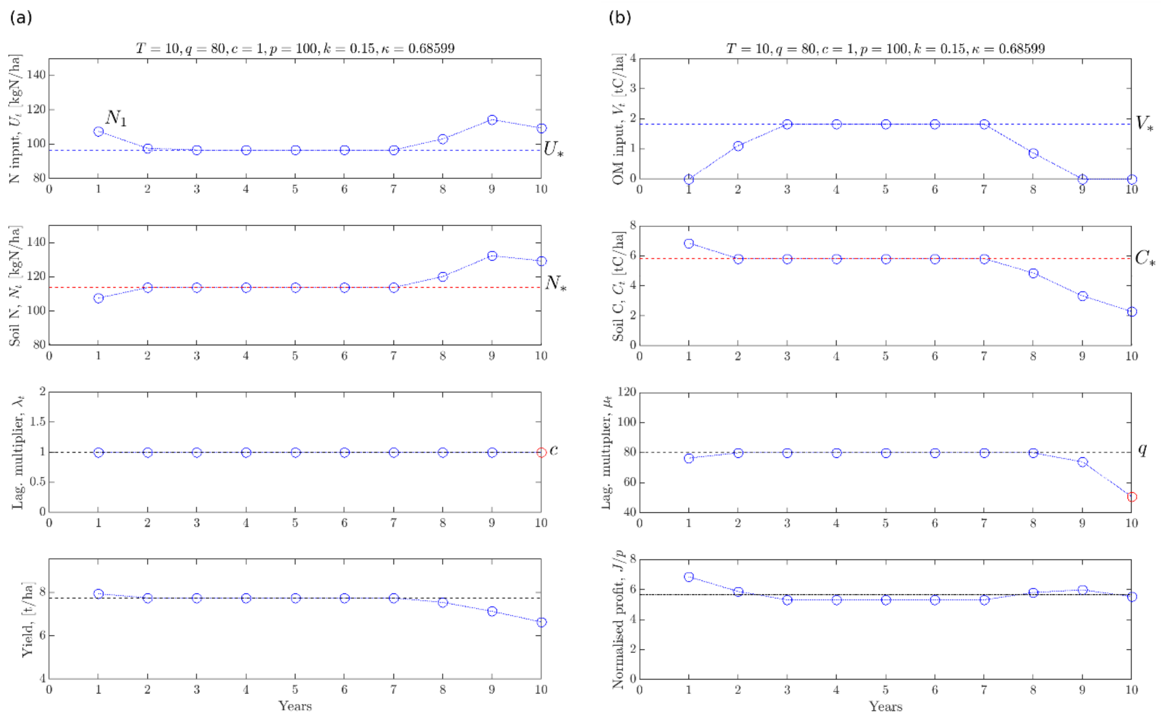


Figure 9, Optimal trajectories of the soil nitrogen and carbon (N_t, C_t) (red lines) and inputs (U_t, V_t) (blue lines). (a) $C_0 = 0$ tC/ha, (b) $C_0 = 10$ tC/ha. These trajectories correspond to those presented as time series in Figure 6 and 4.2.1.2. The numbers labelling each point represent the season numbers. As explained in Section 4.4.1.2, the parts of trajectories made during the final 7,8,9,10 years in (a) and (b) are the same as they depend on the BER dynamics equilibrium point (N_*, C_*, U_*, V_*) only and the end conditions (λ_T, μ_T) in Eq. (23). Note how the dynamics differs from the static BER approach (red circle). Parameter values: $T = 10, q = 80, c = 1, p = 100, k = 0.15, \kappa = 0.686, N_0 = C_0 = 0$.

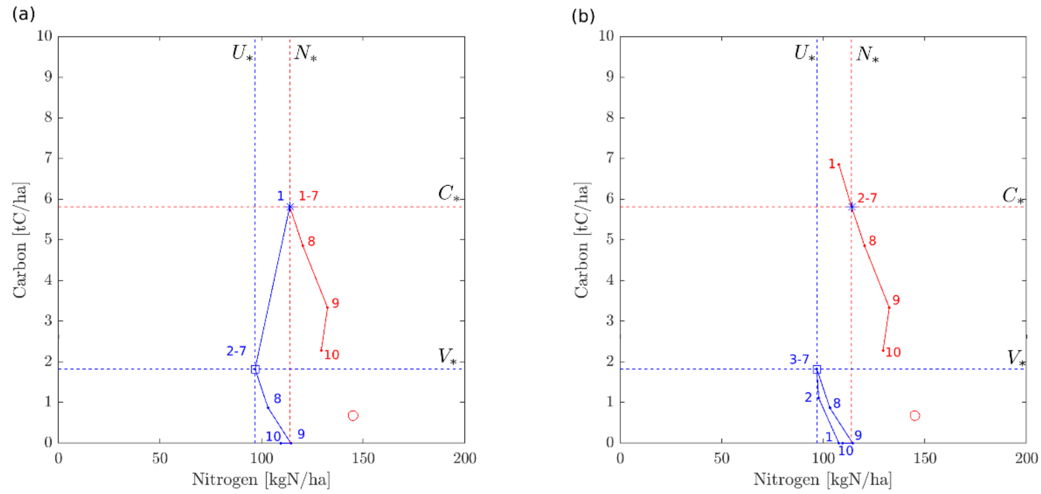


Figure 10. (Left) Effect of the cultivation period T for an OM price $q = 80$ £/tC. (Right) Effect of the OM price for $T = 10$ years. Note the diminishing returns in profit as cultivation period increases. The effect of q is the reverse because the more expensive is the OM, the less is applied, which in turn reduces profit. Parameter values: same as in Figure 6. Parameter values: $c = 1, p = 100, k = 0.15, \kappa = 0.686, N_0 = C_0 = 0$.

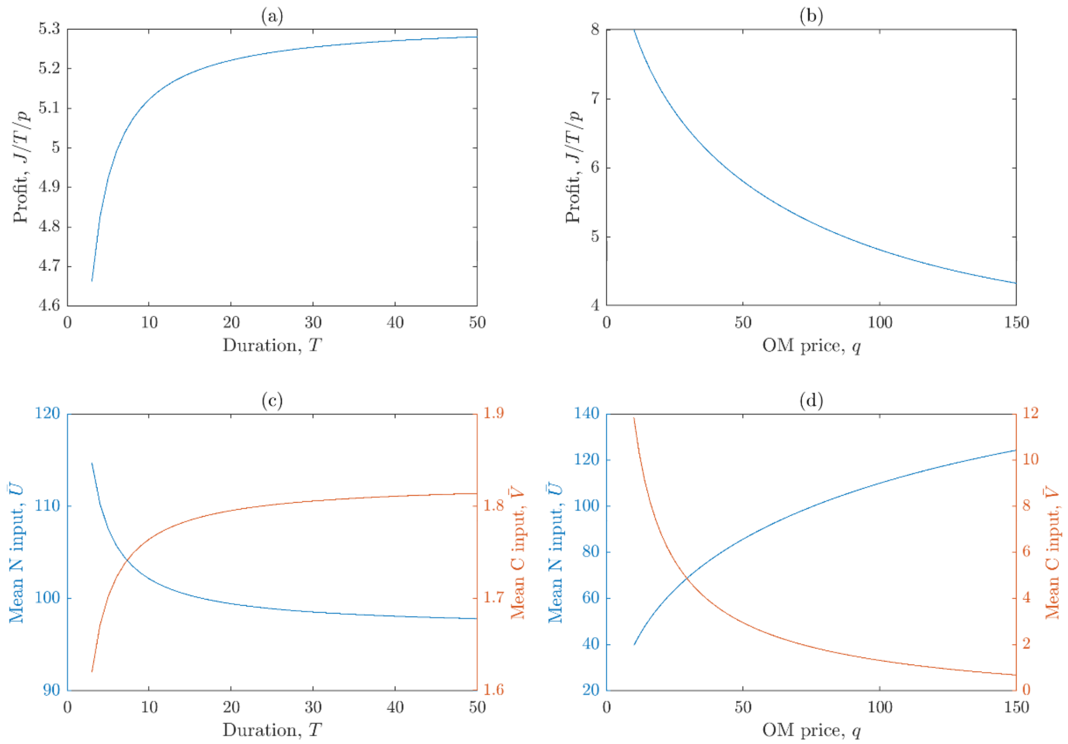
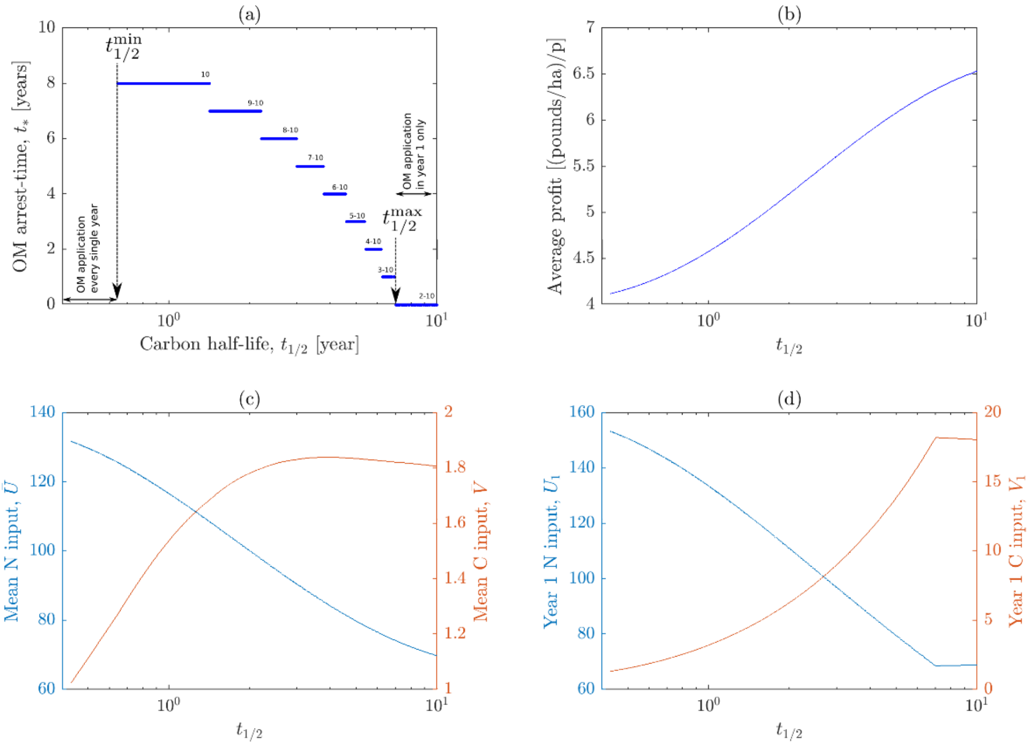


Figure 11. Effect of the carbon half-life $t_{1/2}$ (i.e. decay constant κ). The amendments discontinuation-time t_* is a decreasing stepwise function of κ. See Figure 16 and Figure 17 in the Supplementary Information for examples of optimal trajectories with different κ. In (a), the numbers above the blue lines represent the specific years with no organic matter input. In (d), the hyperbolic increase in the initial OM input comes from the fact that $V_1 = V_*/(1-\kappa)$. Parameter values: $T = 10, q = 80, c = 1, p = 100, k = 0.15, N_0 = C_0 = 0$. Recall that $t_{1/2} = ln(1/2)/ln(\kappa)$.



4.4.2. Results from Rothamsted and Woburn experiments

4.4.2.1. Analysis of data from the Woburn Organic manuring experiment using the linear plus exponential curve

In trials it was found that r_2, c_2 and C_s (Eqs. (8-10)) could be fixed for all data in a series (at Woburn for example) but it was necessary to vary a, b', c and r_1 to take account of the different seasons and crops. Yields were divided by the mean of the zero C plots as described below and curves fitted as described in Section 3.2.4.

Despite these attempts to discover stable parameter sets, the variability in yields during the first experimental phase on the WOM (1972-81, Figure 12) made it very difficult for the fitting routine to converge meaningfully (Table 32). The year to year and crop variability in the second phase was much less and consequently it was possible to compare treatments and derive a value for the rate of decline of the yield-enhancing power of the organic amendments reliably. Both reciprocal and *lexp* curves were fitted to the WOM 1981-94.

The agreement between the values of the rate loss of yield benefit in soils amended with FYM and those amended with straw at Woburn is remarkable (Table 33, 4 significant figures) but most certainly fortuitous. However, it is sign that the method for obtaining parameters has converged reliably on this subset of the data. Note that all 8 years were used in the fitting process here in contrast to Section 3.2.2 where the last 3 years were omitted.

Table 32. Fitted value of the rate of loss of yield-enhancing power of the stated organic amendment compared with the appropriate control. Linear Exponential model 1972-1981, Phase 1 of the Woburn Organic Manuring Experiment

Lexp function. 1987-1994 only Build-up 1981-1986	Number of plots	k_c	Goodness of fit (Sum of Squares)
FYM, Fd[1] control	4	0.0271	21.95
Straw, Fs[2] control	4	0.6518	14.41
Lc,N[3] Fd control	6	0	
Pt, Fd	4	0.461	21.6
Gm	4		

[1]Fd mineral nutrients applied to equivalent levels found in the FYM applied
[2]Fs mineral nutrients applied to the equivalent levels found in the Straw
[3]Leys receiving either Nitrogen fertiliser or grown with clover. See Mattingley (1974a).

Table 33. Fitted value of the rate of loss of yield-enhancing power of the stated organic amendment compared with the appropriate control. Linear Exponential model 1987-1994, Phase 2 of the Woburn Organic Manuring Experiment

Lexp function. 1987-1994 only	Number of plots	k_c	Goodness of fit (Sum of Squares)
FYM, Fd[1] control	4	0.67274	9.407
Straw, Fs[2] control	4	0.6727	6.216
Lc,N[3] Fd control	8	0.6686	22.792

[1]Fd mineral nutrients applied to equivalent levels found in the FYM applied
[2]Fs mineral nutrients applied to the equivalent levels found in the Straw
[3]Leys receiving either Nitrogen fertiliser or grown with clover. See Mattingley (1974a).

Figure 12. Yields of crops relative to the control (not receiving amendment) in the first two (rotational) phases of the Woburn Organic Manuring experiment and showing that leys increased yields more than straw or FYM.

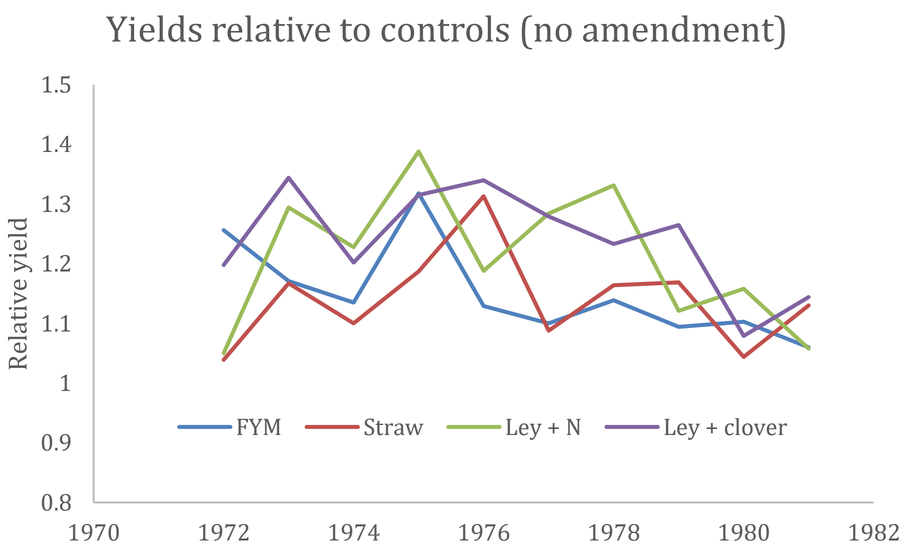
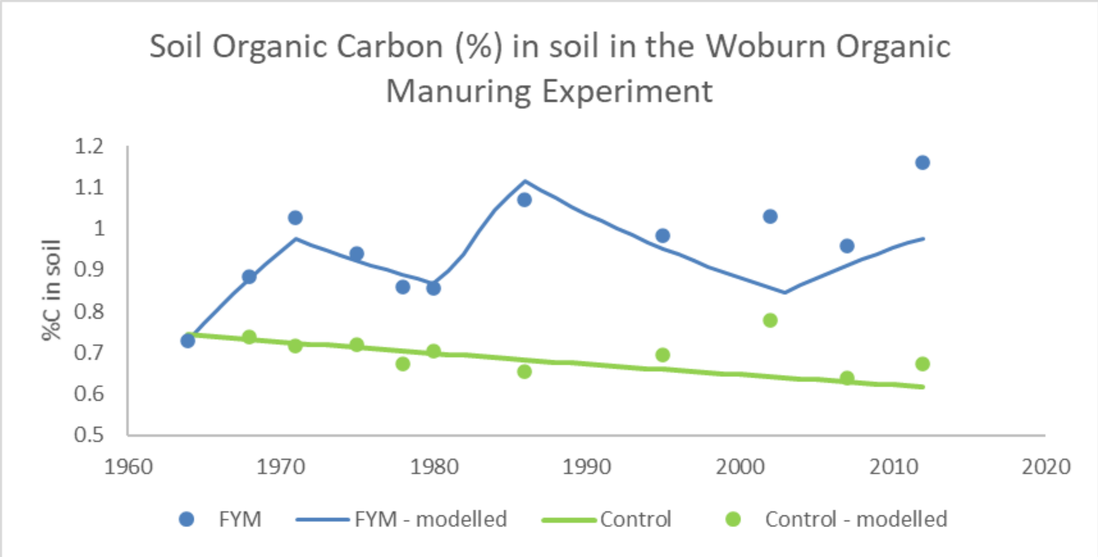


Figure 13. Change in Soil Organic Carbon in plots FYM (Dg) receiving 6 years of FYM prior to 1972 and between 1981 and 1987 and annually from 2004 compared with control plots receiving each year amounts of mineral nutrition (apart from N) equivalent to the that supplied by the FYM. A model based on first order processes was fitted to these data. Rate constants for FYM and native OM (control plots) were 0.042 and 0.0039, respectively. A respiration (loss) parameter was also applied to the FYM on addition with value 0.495 so that almost 50% of added FYM is respired before incorporation into SOC.



The Woburn experiment contains data on the build-up and decline of total C in soil (e.g. Figure 13). This build-up and decline clearly parallels the addition and loss of yield-enhancing power of organic matter in soil, but does not equal it, since we see just as clearly in the results reported on here that yield enhancement fades after 4 or 5 years (Figure 4b) but that it is 10 or 15 years before the additions to soil made between 1981 and 1986 decline to 1980 levels (Figure 13). Thus, organic C in soil (or at least changes in organic C) may act as an indicator for changes in yield, but more work is needed to make this relationship fully quantitative.

4.4.2.2. Analysis of data from the Fosters experiment

Yields from plots receiving organic amendment on Fosters field between 2017 and 2020 continue to be greater than unamended control plots (Figure 14) continuing the earlier trend established with AHDB funding (Whitmore *et al*. 2017) in the same experiment. However, the between years variability is very large and with no obvious increasing trend. The increase in yield in return to application diminishes with input as would be expected (Figure 14). The variability arises partly because the growing conditions differ in each year and partly because different crops were grown. However, the purpose of expressing yields relative to controls is to eliminate as far as is possible these between crop-year differences. Two things are clear in Figure 14 (i) that anaerobic digestate, compost and FYM consistently increase yields above the control after one or two years of amendment and (ii) that straw is less likely to do so. This seems to be due to an interaction between the N-deficient straw and applied rate of N fertiliser as suggested in the figure legend.

Figure 14. Yield increases of OM amended plots relative to controls on Fosters field between harvests made in 2013 and 2019. Two crops were grown each year until 2016. Relative yields were calculated from the mean yield of the amended treatments across all N rates divided by the mean of the control plots across all rates of N applied. The N supplied by ad, FYM and compost may inflate these means at low rates of applied N. In contrast, the lack of N in the straw amendment decreases these means at low rates of N applied.

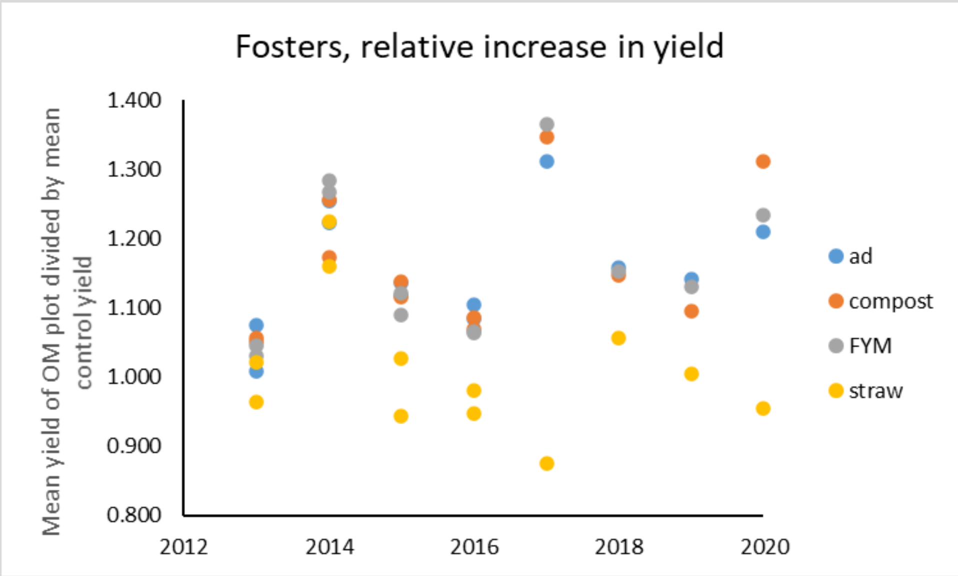
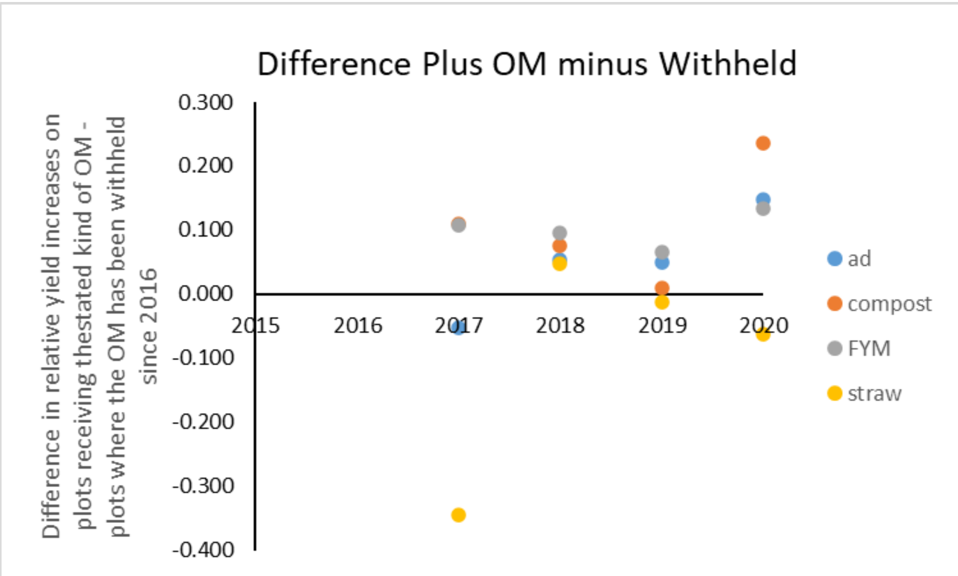


Figure 15. Comparison between plots with and without continuing amendment of yields relative to controls on Fosters field 2017-2020.



Our expectation was that where amendments were withheld starting in the autumn of 2016 for crops harvested in 2017, the yield benefits of OM amendment would decline. If this were the case the difference between plots continuing to receive amendment and those without would increase. This proved not to be the case (Figure 15). Yields on unamended plots matched, and in some cases exceeded yields, on amended plots. It is not easy to explain these data. The results are consistent with the idea that amending soil confers a long-lasting physical improvement such as the reduction of bulk density that deteriorates slowly. However, the result is at variance with data from WOM where a rapid decline in yield benefit was observed. It is possible that the silty clay loam Batcombe series soil at Rothamsted where the Fosters experiment is located, behaves differently from the Cottenham series sandy loam at Woburn. The experiment continues and it is possible that the looked-for difference will eventually arise.

4.4.3. Rotations

Rotations can be modelled in a manner analogous to the above recipe for organic amendment. In Eq. (29) below, the expression $r\sqrt{n}$ replaces C the organic matter content in Eqs. (1-2). The constant P_0 is the baseline and replaces C_s. Parameter r is a constant and n is the number of full rotational sequences. So, for a 3-course rotation practised for 6 years, n would have the value 2; $A, \hat{B}, N_s$ and α are constants as before. N is the amount of nitrogen fertiliser applied. We have

(29)

$$\frac{1}{Y} = \left[\frac{1}{A} + \frac{1}{\hat{B}\left(P_0 + r\sqrt{n}\right)(N_s + N)}\right]\left[\frac{1}{1 - (N_s + N)/\alpha}\right].$$

The relationship $r\sqrt{n}$ here is pure empiricism. No justification can be offered for this, other than it delivers diminishing returns – that is to say, the longer the rotation goes on the less additional benefit accrues per period. However, it demonstrates the principle of the method and provides a metric for distinguishing between rotations.

The Broadbalk field experiment at Rothamsted has been in existence since 1843. Besides the plots that have grown wheat almost every year since, there are series of plots that have grown wheat in rotation. In particular, for 12 years between 1968 and 1980 two rotations were tested: (i) potatoes-wheat-beans, (ii) fallow-wheat-wheat. Any benefits to wheat as a result of rotation might be because the other crops in the sequence add nutrients (legume) or organic matter, or suppress disease (especially take-all) or weeds. Alternatively, the way land is managed might suppress wheat yields by compacting soil or delaying the date on which wheat might otherwise be sown.

Table 34. Value of r the rotation factor in Eq. (29) that describes the value of the rotation to wheat crops compared with a continuous wheat control

Rotation	r rotation factor
Potatoes-wheat-beans	0.707
Fallow-wheat-wheat	0.226
Wheat-wheat-wheat	0

The value of potatoes and beans in a 3-year rotation can be seen to have an impact on Eq. (29) of more than three times that of a single a single fallow (Table 34). Actual yields obtained depend on other factors in Eq. (29). In practice on Broadbalk, the impact of the fallow on wheat yields during this period was next to nothing but the beans and potato rotations raised yields by about 1 t/ha on plots given the largest rate of N tested (192 kg N/ha).

4.5. Discussion

The methodology derived for this report describes a means to put the multi-year response of crops to more than one input on a sound rational basis. The extension of the well-known Break-Even Ratio to the economic response of crops to applications of Organic Matter during several years as well as to applications of N is a valuable addition to the farmer's and agronomist's recipe book. However, it cannot be denied that the methods are difficult and that they generate additional choices. The increase in choice and decision-making is an inevitable result of the increase in dimensionality of the problem. The nitrogen BER deals with a single input; our methodology deals with two or more inputs over a number of years. That number is one of the extra decisions that need to be made. A second input such as organic matter as well an extended timeframe brings still more factors into play such as the year-to-year change in the price of the OM. For these reasons it is difficult to present a table of BER values that suggest how more or less N a farmer should apply in relation to the price of wheat or fertiliser. The cost of OM and the timeframe also need to be considered. In principle our methodology could be programmed into an app or advisory software. In practice the rule of thumb that we present may be a reasonable approximation.

The rule of thumb assumes that there is a kind of equilibrium or maximum level of yield increase that can be achieved by adding OM to soils. In the framework developed here, this equilibrium is determined by Eqs. (27-28). In practice, our analysis suggests applying the equilibrium amounts (U_*, V_*) of fertiliser and OM amendments. As shown in Supplementary Information (Figure 21 and Figure 22), the profit maximising optimum trajectory (Section 4.4.1.2, Figure 7) can be approximated by applying the amount U_* of fertiliser every year for the whole cultivation period T, whilst applying amendments at the V_* level for $T-2$ years. The `exact' amounts (U_*, V_*) and timetable of amendments depend on the decay constants (k, κ), which are soil (and crop) properties but can be determined in principle using the methodology described in Section 4.3.2. It seems possible that such a steady state may be related to the equilibrium level of the *amount* of organic matter that can be built up in soil. Again, we cannot be sure, but the way to avoid extensive experimentation as is necessary to establish the response of crops to N and thus the N BER ratio, would seem to be to relate these two OM equilibria, i.e. relate the yield-enhancing carbon to the overall amount of soil carbon. If this could be achieved for different soils it would allow the economic yield benefit from amending soil with OM to be inferred widely, easily and at relatively little expense.

The analysis and procedure presented in this report is intended to build on the existing guidance that is based on *economic* optima. However, at the time of writing the economics of organic amendment in terms of consistent pricing is unclear. The adopted prices of organic materials may seem on the high side however, the prices can vary from zero to considerably more than we suggest. Our prices factor in transport and spreading costs which are considerable because most amendments contain substantial amounts of water that bulks up the product and which also costs money to transport. Acquisition prices and spreading costs are not normally included in the nitrogen costs. Fertiliser is a dry product so that delivery can be factored into a price uniformly around the country. In general application costs are not included in current fertiliser guidance. Clearly much of this could change if large-scale drying technologies became available. A farmer who has an AD or compost plant next-door will not face the haulage costs of a colleague many miles distant. Without certainty as to these prices it is not possible to give certainty as to the economically optimum strategy for the deployment of organic materials on farm. Our method gives the strategy for doing so when key parameters such as the cost of amendment applied to land and their rate of persistence in soil are known (i.e. parameters q, κ).

The conclusions and any eventual system of advice depend on the underlying understanding of the response of crops to the inputs. We explore two response curves in this report: an extension of the linear plus exponential model (George 1984) and the reciprocal method advocated by Greenwood for horticulture in the 1970's. Of the two, Greenwood's extends most logically to two or more inputs: they are added as reciprocal terms. The interactions between inputs (terms) are prescribed by the structure of the reciprocal function. However, we found it necessary to introduce an additional interaction term to ensure that the curve turns over in the same way that the linear component ensures a downturn in the linear plus exponential (lexp) function. The extension suggested here to the *lexp* method itself is somewhat arbitrary. It should be noted that it has been developed for this project and unlike Greenwood's curve has no sound provenance. Indeed, it differs from earlier suggestions for such curves (Whitmore *et al*. 2017). An extension to other nutrients would be possible but the need to introduce interaction terms explicitly is likely to lead to a cumbersome formula.

There can be little doubt that measuring the increase in yield that comes about as a result of amending soil with organic matter is fraught with difficulties. Hijbeek *et al.* (2016) went as far as to conclude that there was no or little increase in yield on amending soil over and above what could be accounted for by the extra minerals the amendments contained. Potatoes were a possible exception to this observation. That is not the case in either the Fosters or WOM experiments. Here, nutrients including N were carefully accounted for and in earlier work (Mattingley *et al*., 1974) used explicitly to adjust the response curve N axis and so eliminate any effect of added mineral N from the amendment on yield response. There is little doubt that the yields are variable, however, and even under the carefully controlled conditions in both Fosters and WOM this variability makes it difficult to fit models and so extract important parameters of interest such as the rate of build-up and decline of the yield-enhancing effect of added OM. As more data is collected this should become possible. Figure 14 and Figure 15 illustrate this variability and the difficulty faced in fitting a curve with confidence. The data from the second phase of the WOM experiment (Figure 4(b)) have been useful in this respect. We do not know why Hijbeek *et al.* (2016) found little response of crops to OM. It may that their otherwise extensive survey of crops did not include crops from the UK. The UK's maritime position and growing season that continues through the winter or that starts early in spring may in some ways account for the different observations.

The methodology developed in this report allows a rationale for pricing field fertility from the concept of the Lagrange multipliers. As hinted in Section 4.3.1.1, the Lagrange multipliers represent the price of a unit increment in fertility, quantified in terms of yield-enhancing power of soil nitrogen and carbon, that corresponds to an increment in profit. At the BER the unit increase in fertility just equals the unit increase in profit, as is well-known. We found that optimal trajectories are governed by a dynamical equilibrium (resulting from the balance between inputs and annual losses assumed from the recurrence equations (18)) for which the nitrogen and carbon Lagrange multipliers, namely λ and μ, must be equal to the marginal costs (c and q) of their respective inputs. To a factor set by the annual losses of N and C (inverse of $1-k$ and $1-\kappa$), equilibrium values of λ and μ also equate to the marginal return from cropping governed by the shape of the response curve (Y_N, Y_C), Eq. (27). All this is very reminiscent of the classical BER approach advocated in the AHDB guidance. But, in the optimal dynamics solution (Section 4.4), the system adapts itself automatically to the internal dynamics of fertility such that the shadow prices of nitrogen and organic matter become equal to their respective marginal costs. As a result, amendments must be stopped towards the end of the timeframe so that the shadow prices of fertility continue to equal the marginal returns allowed by the state of fertility in the final year T (i.e. these are the boundary conditions in Eq. (23)). As clearly showed in Figure 11, the fertility levels and inputs scheduled along such optimal trajectories are strongly governed by the rate of loss, $1 - \kappa$, of the yield-enhancing carbon. This is no surprise, since this is a key assumption underlying our approach. However, despite the simplicity of our ‘soil fertility dynamical model’ (uncoupled linear recurrence equation Eq. (18)), our approach captures the essence and reveals the complexity of the dynamics of fertility. It clearly demonstrates that the change in time of fertility cannot be overlooked in developing optimal guidance in the application of fertilisers that persist in soil and organic amendments to crops.

4.6. Conclusions

In answer to the questions posed in the introduction it seems clear that apart from the first and final two or three years it makes sense to apply a constant rate of organic amendment to soil. This amount will depend on the nature of the material, its longevity in soil and the economics of its acquisition and spreading

- At first sight the stipulation that field-specific OM response curves are needed to make full sense of the research reported here might make the results seem of little value to farmers. However, many N response curves have been collected in trials during the last 40 years with the express purpose of supporting periodic revisions of the fertiliser guidance manual, devised originally by Defra (MAFF, reference book (RB209)) and now published by AHDB. The apparent congruence between the change in organic matter contents (or at least increases as a result of amendment) and increases in yield, suggests a more pragmatic and cheaper alternative. A relatively small series of OM trials could establish the build-up and longevity of the yield-enhancing effects of OM and compare this with the physical build-up of OM in different soils. The aim would be to establish the equilibrium target values (Section 4.3.5).
- Results from the WOM experiment Rothamsted (Section 4.4.2 & Mattingley, 1974) appear at first sight to contravene results from elsewhere in the Rotations Research Partnership. Amendments such as FYM increased yields more that cover crops. This apparent contradiction can perhaps be explained by other treatments within the WOM trials. Several grass ley treatments were included; these yielded rather more than the FYM, peat/compost or straw-amended plots and the yield increases persisted for longer (Figure 12), even though the amount of organic matter and carbon put into soils from the leys was almost certainly substantially less than was the case from the amendments. Mattingley *et al*. (1974) observed that the bulk density on the ley plots was rather smaller than on the other plots. The relatively greater yields may well have been an effect of this difference in bulk density. This is reasonable because it seems likely that the mechanism by which organic matter enhances yields is by reducing the bulk density and so increasing the diffusion of oxygen into soil, the passage of water out of the soil when wet and the amount of storage of water in the soil at dry potentials. Seen in this light, the yield enhancing qualities of organic amendment and leys of cover crops result from the activity of roots as they grow and reorganise the structure of the soil to suit themselves and the plant. This hypothesis that plant roots and other soil organism re-organise soil structure to their combined benefit is consistent with the otherwise odd observation that overall density *increases* in direct drilled soils, yet drainage, rooting and eventually also yield increase. The latter benefit, however, can take time to develop.
- Our analysis in this project has been to try to set advice on the use of OM amendments and other OM-enhancing treatments on the same basis as the advice for nitrogen. Accordingly, we reckon over a time period during which we expect all of the applied OM to have

decomposed or until the date by which all of the economic benefits expire. However, it is possible to reckon over other timeframes especially shorted ones. For example, improvements (or deterioration) to land may result during a one-year tenancy. In theory, an economic value to the improvement or cost of the deterioration is factored into the price agreed for rental. In practice, such costs and prices are very hard to decide upon. Our methodology could attribute a value or a price for the different ways in which land is managed over time. The purpose of rotational cropping (below) is to impart exactly such an improvement and increased value to soil during a set timeframe. This benefit is usually expressed as the increase in yield to a particular crop – usually one such as wheat that succeeds a break crop that builds fertility or breaks a pest or disease cycle. However, the value of the rotation may be greater than this, especially where other properties of land are being considered. The methodology presented here does not articulate how to value ecosystem services other than production, but it does set out a firm basis of what to do with that valuation over time and in relation to other valuations of the function of land that might applied simultaneously – the ability to store carbon, for example, alongside its ability to grow high-yielding crops.

- Rotations can be modelled and quantified in a manner similar to the way we have treated organic matter. The fuller rotational sequences, the more yield can be expected to increase relative to a crop of interest that is not grown in rotation. Where a strict control is missing and unlikely to ever exist, continuous potatoes, for example, the yield of the crop of interest within other sequences can be compared. A better response-to-rotation curve is needed, however, or at least one that has been shown to be better than others. The square root function adopted here within a reciprocal response to N curve is intended to be illustrative only. Although not explored within the current project, rotations clearly leave the soil in different states at the end of a full sequence. Just as we suggest that residual value might be attributed to a well-managed rental compared to those managed less well, so a good rotation will have a residual benefit and value compared with a poor one.
- The mechanism by which added amendments enhance yield is still not clear. Initial results suggested that the increase and decrease in yield benefit paralleled the increase and decrease of % carbon in soil. Whilst it is clear that both increase and decrease at the same time, it is apparent that they do not change at the same rate. %C in soil persists for longer. It is possible that it is particular fractions in the OM that provide the yield benefits. There is an indication that the more energy (calorific value) an amendment has the more able it is to increase yield. These energetic components of amendment would be likely to be the fraction most readily and most rapidly exploited by soil organisms – possibly in the service of increasing yields. An alternative explanation is that it is the continuous release of one or more nutrients from the amendment that affects yields. Nitrogen fertiliser, for example, is applied in one or two splits in the spring. Available N from the decomposition of the amendment all year round would supply low levels of nutrients to a crop that might explain increases in yield. It is hard to reconcile this view with two other observations however: (i) straw and FYM benefit yield similarly, but the straw contains much less N and (ii) the leys and the green manures supply much N in relation to the amount of carbon, but the absolute amounts of N delivered are much less than from FYM. The ley treatments increase yield by the same amount as FYM in the Woburn Organic Manuring experiment in Phase 2 and by rather more in Phase 1. The relatively energetic straw might be expected to increase yields more than FYM, however, and this is not straightforward to explain unless it is a combination of energy content and continuous nutrient supply that delivers the observed benefits in yield.

- Inputs such as P that are not fully consumed by the plant in the year of application might be expected to behave in the same way as OM. P is usually maintained in soil above thresholds or within ranges of values. It is possible that P nutrition is slightly more complex because diffusive transport through soil to the roots is much slower than the more mobile N and because P adsorbed to soil is not a consistent quantity with definite release characteristics. Nonetheless, P supply should be amenable to a similar control approach.

4.7. Acknowledgements

Data from the Woburn Organic Manuring experiment were supplied by e-RA: Electronic Rothamsted Archive, Rothamsted Research.

4.8. Supplementary Information

4.8.1. Effect of κ on the optimal trajectory

To illustrate the effect of the carbon decay constant and contrast with the optimal trajectory described in Section 4.4.1.2, we present in Figure 16 and Figure 17 two examples for which the carbon dynamics is slower than the one determined with the Woburn data (Section 4.3.2.2), i.e. $\kappa > \kappa_{\mathrm{Woburn}}$. Numerical calculations yield smaller amendments discontinuation-time $t_* = 4$ years and $t_* = 0$ year for $\kappa = 0.85$ and $\kappa = 0.92$ respectively (also see Figure 6(a) in Section 4.4.1.2). The larger the decay constant κ, the more yield enhancing carbon is carried over from one season to the next. In turn, the smaller is the discontinuation-time t_* because of the combined effect of the increase of the dynamic equilibrium C_* and the increased slowness of the soil carbon decay associated a larger value of κ, the less the carbon is lost and, the fewer the number of OM applications. These variations of κ for relatively large values of κ (> 0.7 say) have a strong impact on the discontinuation-time, as shown in Figure 11(A). However, this is not the case for the average level of OM input over the total cultivation period T, which remains fairly constant at about 1.8 tC/ha per year. This results in having to apply larger and larger amount of OM over a shorter and shorter period of time as the kinetics of carbon loss slows down. In the two examples in Figure 16 and Figure 17, we see that the need to apply large amount of carbon can cause an economic loss in year 1. Over the long term, the total profit is however still maximised. Our numerical results even show that the slower the carbon kinetics the larger the total profit (Figure 6(b)). The longevity of carbon in the soil improves the profit.

However, there exists an environmental cost associated with this in terms of fertility. In Figure 18, we show how the yield-enhancing carbon ratio C_T/C_* varies with the carbon decay constant κ. For values of the decay constant that we expect for most soils ($\kappa_{\min} \leq \kappa \leq \kappa_{\max}$), our numerical simulations show that the terminal yield-enhancing carbon level C_T cannot exceed 40% of its dynamic equilibrium C_* (Figure 18). We recall that this result is independent of the length of the cultivation period T. The decay in yield-enhancing carbon, triggered by the arrest of organic amendments, is even more pronounced for soils characterised by a very slow carbon decay $\kappa > \kappa_{\max}$, i.e. with a half-life over 10 years.

Figure 16. (a) Nitrogen and (b) carbon optimal trajectory for $\kappa = 0.85, t_{1/2} = 4.3$ years. The time schedule for nitrogen and carbon amendments still divides into three successive portions as explained in Section 4.4.1.2. In this example, OM amendments can be stopped relatively early ($t_* =$ 4 years) because the dynamics of carbon is assumed to be slower than the dynamics determined for the Woburn data. More carbon can accumulate in the soil. Parameter values: $T = 10, q = 80, c = 1, p = 100, k = 0.15, \kappa = 0.85, N_0 = C_0 = 0$.

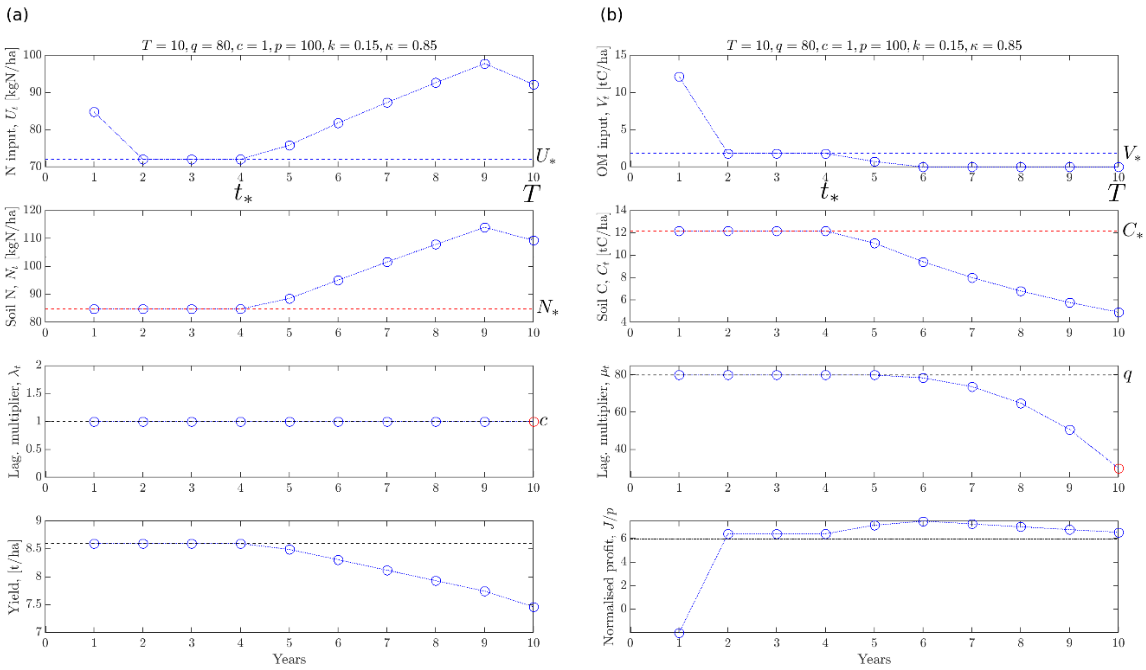


Figure 17. (a) Nitrogen and (b) carbon optimal trajectory for $\kappa = 0.92, t_{1/2} = 8.3$ years. The time schedule for carbon amendments is different from the case discussed in Section 4.4.1.2: amendments are applied in the first year only. About 20 tC/ha would be required to maximise profit over 10 years, which is probably not realistic. Parameter values: $T = 10, q = 80, c = 1, p = 100, k = 0.15, \kappa = 0.92, N_0 = C_0 = 0$.

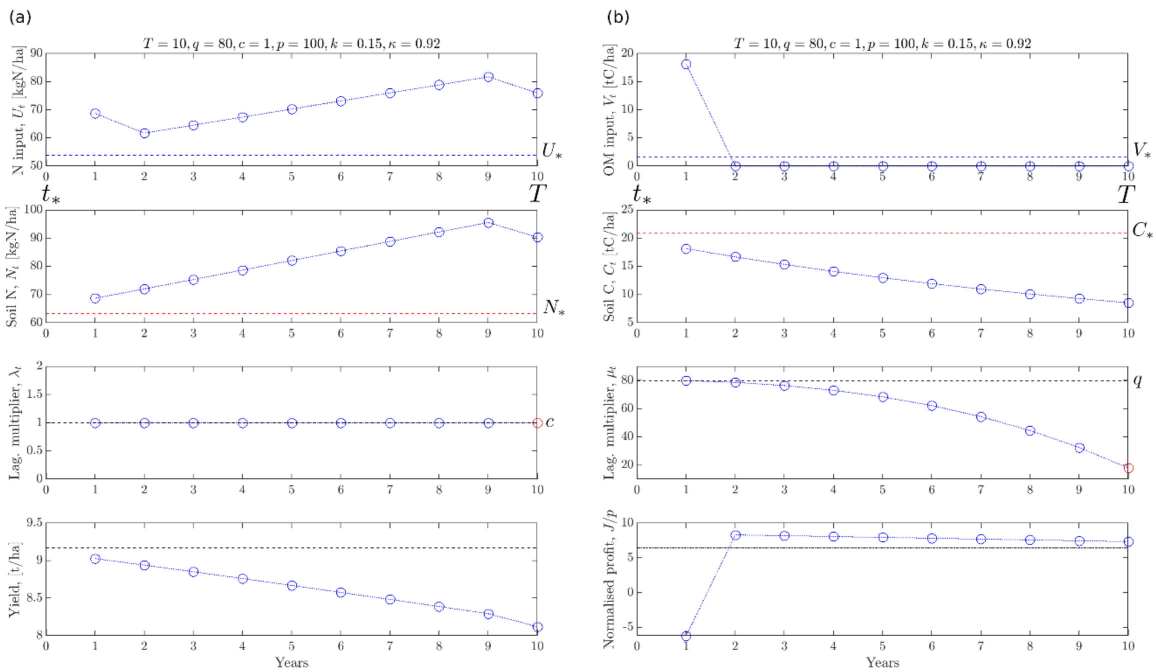
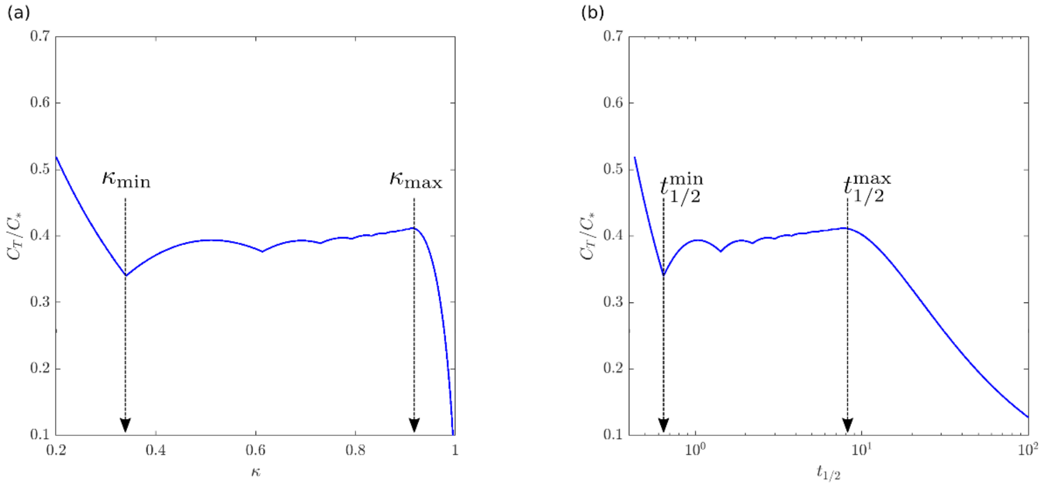


Figure 18. Effect of κ on the terminal yield-enhancing carbon ratio C_T/C_*. Note that this ratio cannot exceed 40% for the range of soil carbon decay constants that we expect for most soils, $\kappa_{\min} < \kappa < \kappa_{\max}$. This loss of carbon reflects the arrest of amendments. Parameter values: $T = 10, q = 80, c = 1, p = 100, k = 0.15, N_0 = C_0 = 0$.



4.8.2. Effect of bounded input rates

Formulation. The optimal trajectory that we described in the main body of the report (Figure 8) is specific to the case where there is no additional constraint on the control variables U_t, V_t, apart from being non-negative. By contrast, interesting cases of practical importance arise when fertiliser and organic amendments applications are limited, for instance because of environmental regulations (NVZ rules) or practical reasons. Mathematically, this means that the domain of admissible controls is bounded. A simple example of such domains is the rectangular domain

(A.1)

$$\Omega(U, V) = \{(U_t, V_t) \in \mathbb{R}_+^2 | U_t \leq U, V_t \leq V\},$$

where U and V represent the maximum input rates of nitrogen and carbon which are permitted to be applied each season. (Note that these maximum rates could be made time-dependent for more generality if necessary.) The domain Ω is often referred to as the *control set* and the conditions $0 \leq U_t \leq U$ and $0 \leq V_t \leq V$ as *inequality constraints*. A boundary of the control set is said to be *active* whenever a control variable is equal to one of the endpoints of the intervals defining Ω. Typical problems to solve are to find critical times at which an optimal trajectory hits or leaves the boundaries of the control set. In our case, such times correspond to switches between applying or withholding OM.

Mathematically, the two inequality constraints must be associated with two Lagrange multipliers and must be included into the Lagrangian function (21) defined in Section 4.3.4.2 by adding the term $\sum_{t=1}^{T}[\gamma_t(U - U_t) + \eta_t(V - V_t)]$. In turn, this modification of the Lagrangian function implies that Eq. (25) becomes

(A.2)

$$\gamma_t = \lambda_t - c + \zeta_t, \qquad \eta_t = \mu_t - q + \xi_t,$$

while the conditions

(A.3)

$$\gamma_t \geq 0,\ \gamma_t(U - U_t) = 0,\ \ \eta_t \geq 0,\ \eta_t(V - V_t) = 0,$$

must be added to the complementary slackness conditions (26). From Eq. (26), we recall that the multipliers ζ_t, ξ_t are zero if the fertiliser and amendments are applied ($U_t \neq 0, V_t \neq 0$).

Conditions for application. It follows from (A.3) that expressions (A.2) reduce to

(A.4)

$$\gamma_t = \lambda_t - c > 0, \eta_t = \mu_t - q > 0,$$

whenever the boundaries of the control set are active with $U_t = U, V_t = V$. That is fertiliser and organic amendments are applied at their maximum permitted rates. Inequalities (A.4) imply that the nitrogen and carbon shadow prices λ_t, μ_t become larger than the nitrogen and carbon prices c, q. This contrasts strongly with the unbounded optimal trajectory shown in Figure 7 and Figure 8 for which the shadow prices are at their dynamic BER values $\lambda_t \equiv c, \mu_t \equiv q$ for most seasons ($t \leq t_*$). The constrained case (Eq. (A.4)) i.e. reminiscent of the two-dimensional static case (Eq. (17)) where inputs belong to the profitability domain $\overline{\Omega}$ and $\gamma, \eta > 0$ (Figure 5(b)). In this case, it the profit could be increased further if one were to increase the rates of inputs (Secs. 3.3.2, 4.1.1.). In the input-limited dynamic case, we expect that a constrained optimal trajectory (while still maximising profit under the constraint of limited inputs) will not lead to the absolute maximum of profit pertaining to the system, which would be the profit associated with the unconstrained optimal trajectory described in Section 4.4.1.2. The Lagrange multipliers γ_t, η_t quantify dynamically how far an input-limited optimal trajectory is from the unconstrained optimal trajectory we described at length in the report. The multipliers γ, η play the same role in statics once inputs are limited. The same reasoning applies for nitrogen (see below).

Discontinuation of Amendments. When organic amendments are stopped $V_t = 0$, we have $\xi_t > 0$ and $\eta_t = 0$ necessarily from (26) and (A.3). In turn the carbon shadow price is $\mu_t = q - \xi_t < q$, as for the unconstrained dynamics (Eq. (25)). As μ_t is below its dynamic BER value, there is no margin left to organic matter applications, which have become too expensive. This shows as a decreasing profit for the subsequent seasons (Figure 18 and Figure 19).

Examples. Figure 19 and Figure 20 show input-limited optimal trajectories both with $U = 80$ kgN/ha but with different maximum organic matter input rates $V = 1.5$ and $V = 3$ t C/ha (□ lines). The unconstrained optimal trajectory (○ lines) is shown for comparison. Here nitrogen must still be applied for the whole period of ten years, but its input rate is locked at its maximum allowed value U. When $V \leq V_*$ (Figure 19), organic matter is also applied at its constant maximum rate V until the amendments discontinuation-time is reached. Note that, in this instance, it is one more year than for the unconstrained case (i.e. 8 years instead of 7). By contrast, because amendments are bounded to a value less than the dynamic equilibrium V_*, the soil carbon cannot be topped-up to its dynamic equilibrium value from year one with a large initial amendment. Instead, the yield enhancing soil carbon increases gradually towards a new dynamic equilibrium $C_+ = U/(1 - \kappa) < N_*$. As the soil carbon rises, yield increases and the organic matter shadow price μ_t decreases as a result. The discontinuation of organic matter amendments is then associated with its shadow price μ_t crossing the dynamic BER value q. It has become too expensive to add carbon compared to the revenue generated from the extra yield, as would be the case for the unconstrained trajectory. The OM boundary of the control set becomes inactive, and amendments are discontinued. When $V \geq V_*$ (Figure 20), similar dynamical effects are observed. However, the increase of the soil carbon towards its equilibrium is faster because more carbon is available to be put into the system. In Figure 19, the OM boundary is active for two years, then amendments are slightly reduced to reach V_* until the discontinuation time t_*.

Interestingly, we see that μ_t decays towards its dynamic BER value q after this initial phase of three years. The rest of this input-limited trajectory is very close to the unconstrained optimal trajectory and behaves in a similar fashion. Note that in this situation, the soil carbon can overshoot the unlimited-input equilibrium C_*. The soil carbon equilibrium is different because the nitrogen $U < U_*$ does permit the soil nitrogen to reach its unlimited equilibrium N_*. Regarding nitrogen, for all seasons, $\lambda_t > c$ and nitrogen is applied at the maximum permitted rate $U_t \equiv U$. Because the dynamics of nitrogen is fast ($k \ll 1$), the soil nitrogen quickly reaches the dynamic equilibrium $N_+ = U/(1-k) < N_*$. The unlimited-input dynamic equilibrium N_* cannot be attained as $U < U_*$.

Note however that the scheduling of nitrogen inputs is much simpler in the input-limited case: a constant rate should be applied each year, compared to the unconstrained case in which rates increase for the last three seasons.

Profit iso-contour map. With the two examples described previously, we saw that input-limited optimal trajectories strongly depend on the boundaries of the control set. In our case, these boundaries are simple and determined by the bounds U, V of the control set $\Omega(U, V)$. Looking at any such optimal input-limited trajectories as parameterised by these bounds, we computed the total profit for a total period of $T = 10$ years while varying these bounds. Figure 21 shows in the (U, V)-plane the profit iso-contour map synthesising the 10-year profit that is achievable for a given set of the economic parameters p, c, q. Compared to the iso-contour map for the static profit optimisation problem (Figure 5(B)), the profit iso-lines have an elbow shape and do not close up to form a well identified apex of profit. Instead, the profit saturates towards the top-right corner of the diagram in Figure 21 and the topography of the profit landscape flattens when the control set limits U, V are large enough. This is because, as we saw in the simulation presented in Figure 20, the input-limited optimal trajectories converge towards the unconstrained optimal trajectory as the bounds U, V become larger and larger. In turn, the profit generated converges to the absolute maximum given by the unconstrained optimal trajectory. We recall that the unconstrained trajectory is characterised by input rates in the first year equal to the dynamic equilibrium values of nitrogen and carbon, i.e. $(U_1, V_1) = (N_*, C_*)$. When the limits of the control set Ω exceed this level, input-limited trajectories have fully converged to the unconstrained optimal trajectory. In this situation, the control set can be seen to be unbounded. This behaviour also explains the right-angle elbow shape of the profit iso-contours. In the situation where $U \gg N_*$ (resp. $V \gg C_*$), the iso-contours are horizontal (resp. vertical) because the nitrogen inputs (resp. organic amendments) tend to the corresponding unconstrained optimal trajectory. From this, we can conclude that stringent limitations imposed on nitrogen applications can be compensated by organic matter amendments, still allowing similar orders of magnitude in profit. Conversely, at high nitrogen inputs that approximate the guidance (AHDB) BER rate, significant gains in profit (>10%) could be achieved from moderate applications of organic matter (< 2 t C/ha). In Figure 21, we highlight five iso-lines (dotted black lines) representing a profit reduction of 0.01%, 0.1%, 1%, 5% and 10% from the absolute maximum profit in unconstrained dynamics. This shows that a large corner of the (U, V)-plane, more than a quarter of this plane, is delimited by the 1% iso-line. In this region, input-limited trajectories are all equivalent in terms of profit; only marginal gains of less than 1%, can be generated. Interestingly, numerical calculation shows that the input-limited optimal trajectory corresponding to the control set $\Omega_* = \Omega(U_*, V_*)$ defined by the dynamical BER rates (blue * in Figure 21) reaches a profit that is only 2% less than the absolute maximum. For practical reasons, it seems to us that this optimal trajectory is the simplest and the best to follow because the fertiliser application rate is constant and fixed to U_* every year, while the amendments rate is fixed to V_* until the discontinuation time is reached (Figure 22).

Figure 19. Low carbon input: comparison of an input-limited optimal trajectory (□) with the unconstrained optimal trajectory (○) for inputs limited to $U = 80$ kgN/ha, $V = 1.5$ tC/ha. Note that the input-limited trajectory has inputs locked on the limits of the control set $\Omega = [0, 80] \times [0, 1.5]$. Parameter values: $T = 10, q = 80, c = 1, p = 100, k = 0.15, N_0 = C_0 = 0$.

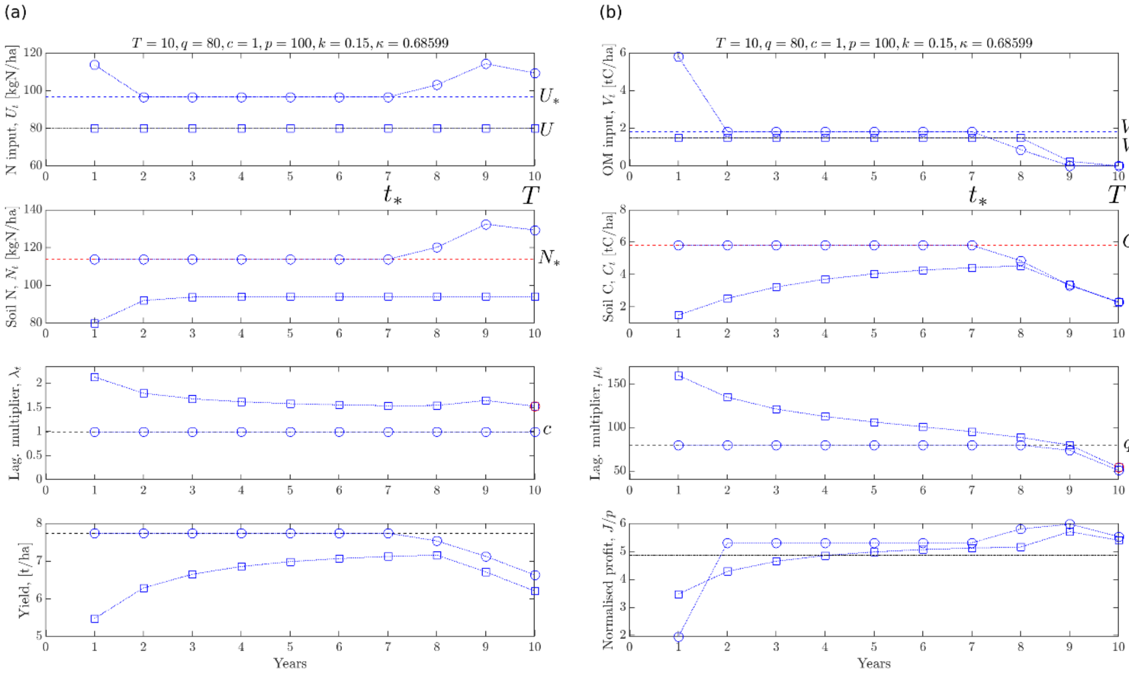


Figure 20. Moderate carbon input: comparison of an input-limited optimal trajectory (□) with the unconstrained optimal trajectory (○) for inputs limited to $U = 80$ kgN/ha, $V = 3$ tC/ha. Note that the input-limited trajectory has inputs not locked on the limits of the control set $\Omega = [0, 80] \times [0, 3]$. The level of amendments allows for reaching the equilibrium. The input-limited trajectory tends to the unconstrained dynamics. Parameter values: $T = 10, q = 80, c = 1, p = 100, k = 0.15, N_0 = C_0 = 0$.

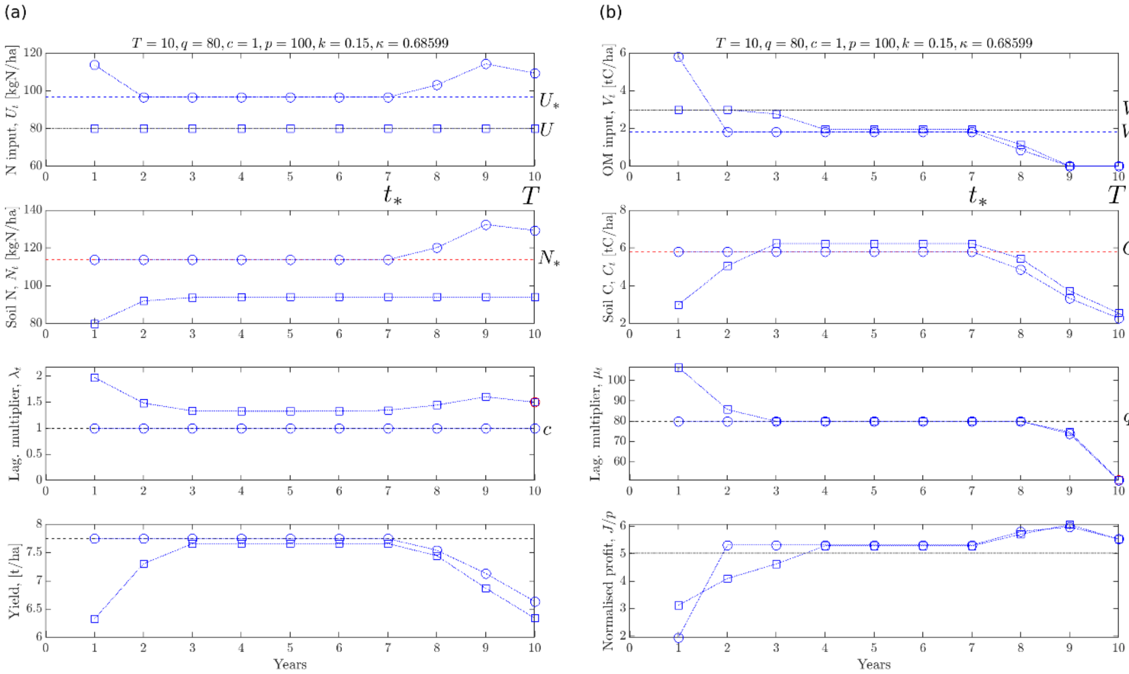


Figure 21. Normalised profit iso-contours for input-limited optimal trajectories. The x and y axes express the maximum (constrained) inputs for N and Y respectively. The iso-lines with percentages highlight the distance to achieving maximum profit. Input-limited trajectories with control sets $\Omega_* = [0, N_*] \times [0, C_*]$ (dynamic-BER limited) and $\Omega_o = [0, N_o] \times [0, C_o]$ (static-BER limited) would lead to about 2% and 10% loss in profit compared to the unconstrained optimal trajectory (blue lines in Figure 22). The Ω_*-limited optimal trajectory (red lines in Figure 22) looks to be a good compromise between achieving high profit with a simple inputs schedule. Parameter values: $T = 10, q = 80, c = 1, p = 100, k = 0.15, N_0 = C_0 = 0$.

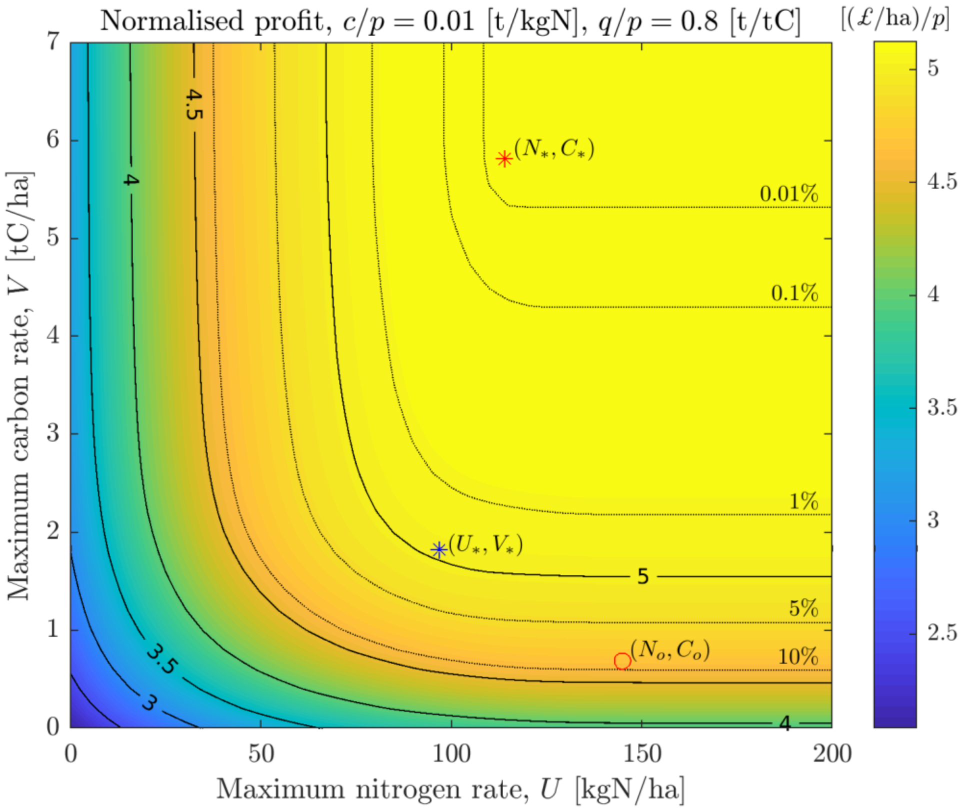
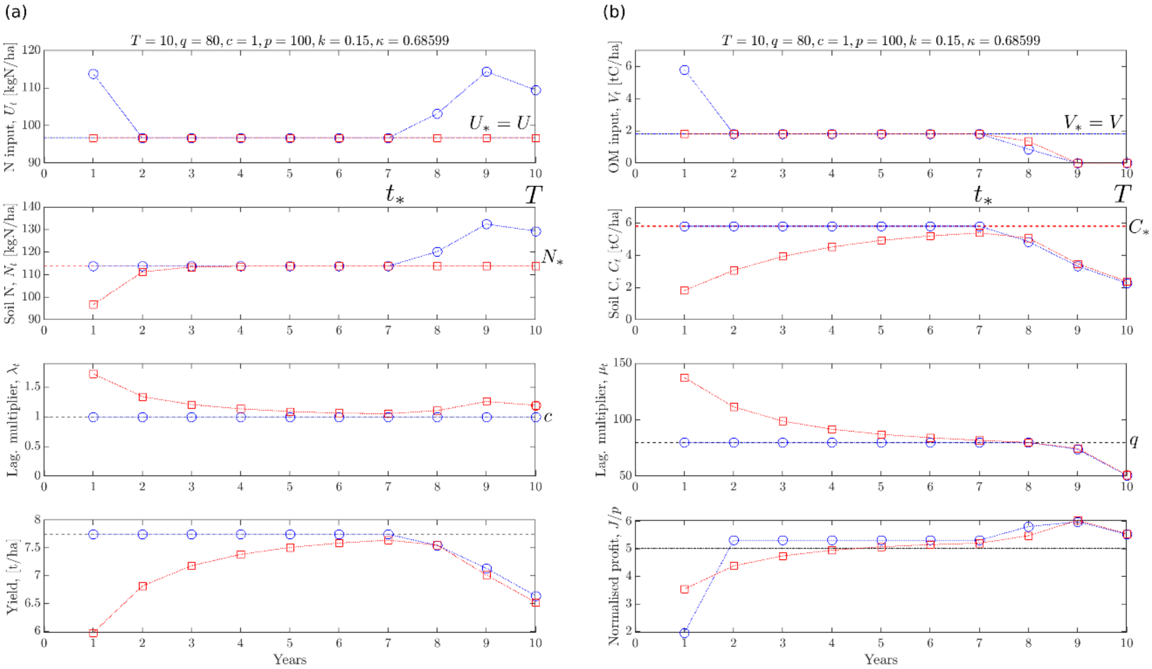


Figure 22. Rule of thumb strategy: comparison of an input-limited optimal trajectory (□) with the unconstrained optimal trajectory (○) for inputs limited to $U = U_*$ kgN/ha, $V = V_*$ tC/ha. The equilibrium input values (U_*, V_*) are defined in Section 4.3.5, Eqs. (27-28). Parameter values: $T = 10, q = 80, c = 1, p = 100, k = 0.15, N_0 = C_0 = 0$.



5. DEVELOPMENT OF THE TERRANIMO® MODEL

5.1. Introduction

Using knowledge on the behaviour of different soils under a range of management practices Terranimo® (Terra-mechanical model) uses computer modelling (https://terranimo.world/choose-a-region) to predicts the risk of soil compaction by farm machinery. The model estimates the risk of compaction for realistic operating conditions. Terranimo® International is the common label for a range of national versions, including a global version. At the start of this project there was not a United Kingdom specific version of this model. The project aimed to expand this global version of Terranimo®, to include detailed information relevant to United Kingdom farmers, including relevant machinery and soil characteristics.

The original Terranimo model was adapted and now includes the following range of features:

- A "Terranimo® United Kingdom" button on the home page leading the Terranimo® United Kingdom version (Figure 23).
- A link from "terranimo.uk" to the Terranimo® United Kingdom version.
- Access to a list of typical soil types for Scotland: this facilitate the choice of the soil type for simulations of traffic situations general for Scotland, or if the soil type proposed from the soil database (see iv)) is not appropriate (Figure 24).
- Soil type selection using a direct access to the Scottish soil database through geographical coordinates chosen manually or on a map (Figure 25).
- Soil type selection using a direct access to the England and Wales soil database through geographical coordinates chosen manually or on a map.
- In addition to this specific UK version development, the AHDB project contributed partly on the general features accessible for all Terranimo® national versions:
- Addition of new machinery: a self-propelled potato harvester is now included as well as three tracked machines (two tractors and a combined harvester) (Figure 26 and Figure 27), which many UK farmers are using, and the addition of a non-symmetrical potato harvester.
- Assessment of the soil compaction risks that includes the impact of repeated wheeling - so the impact of each wheel passing in a given track can be considered (Figure 28).

Figure 23. Terranimo website front page with new United Kingdom "feature"

Figure 24. Access to Scotland specific soil types

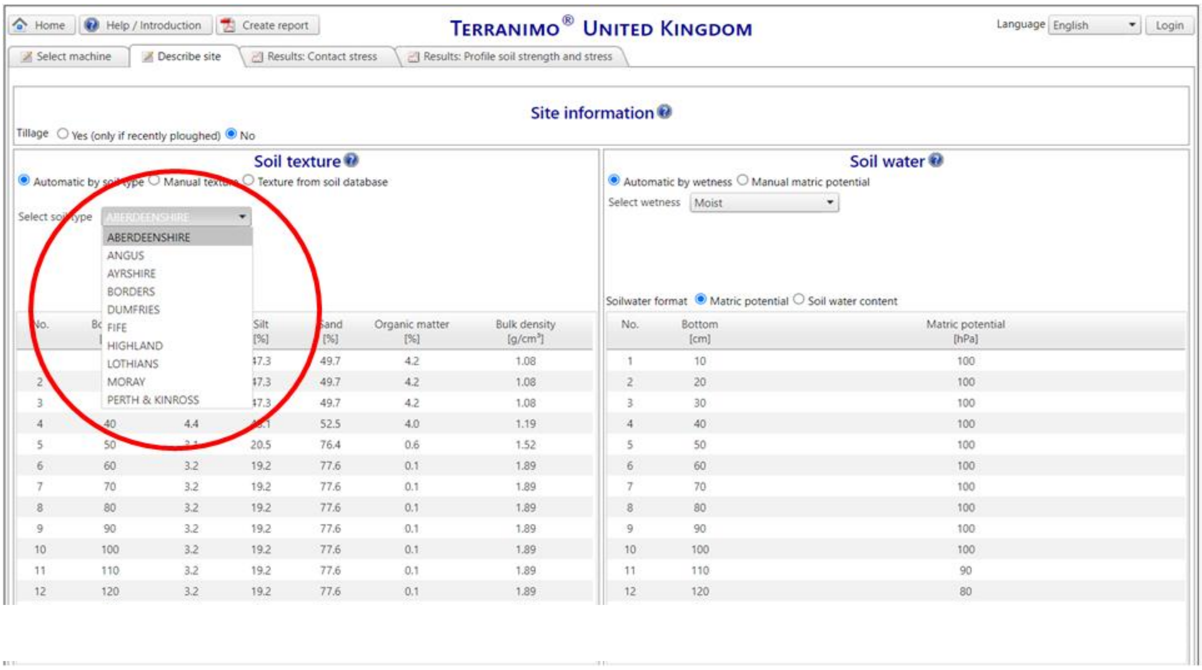


Figure 25. Access to Scottish soil database through geographical coordinates chosen manually or on a map.

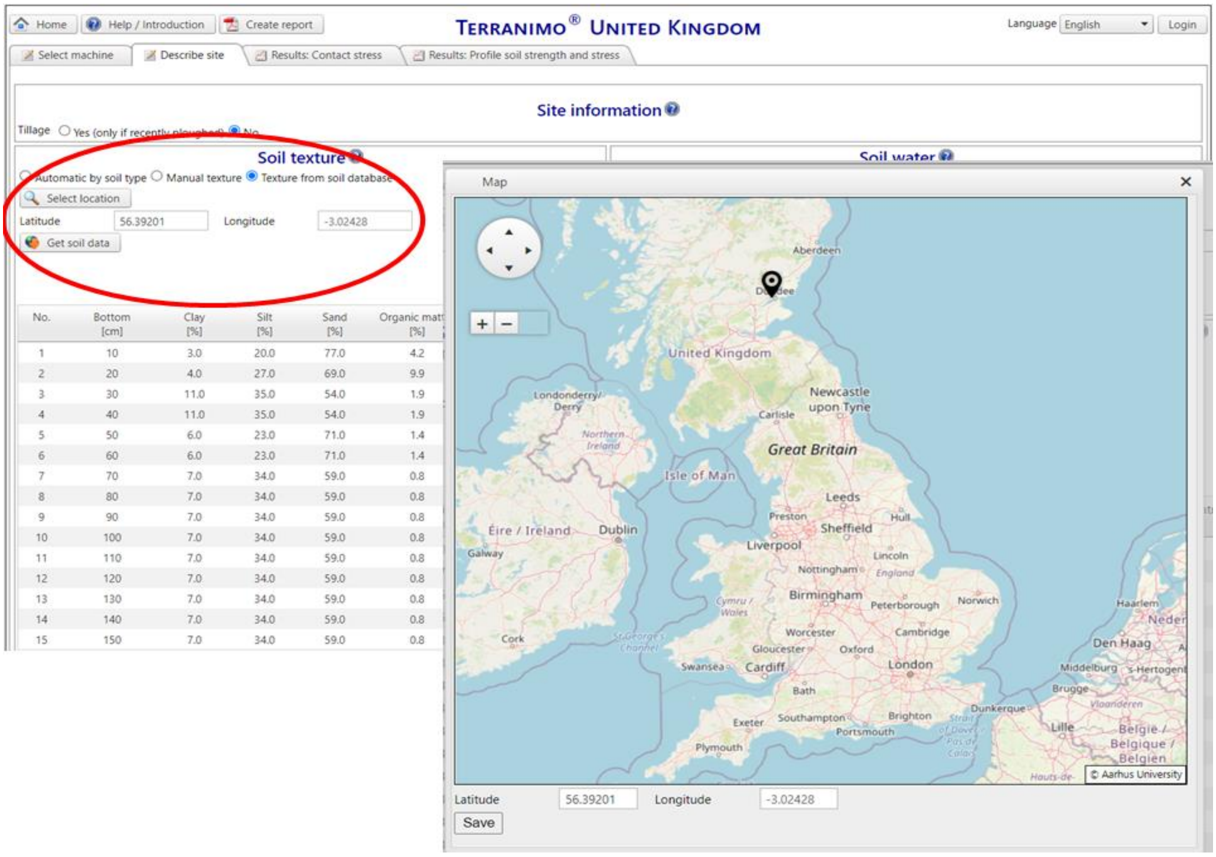


Figure 26. Addition of new machinery (e.g. Potato harvester).

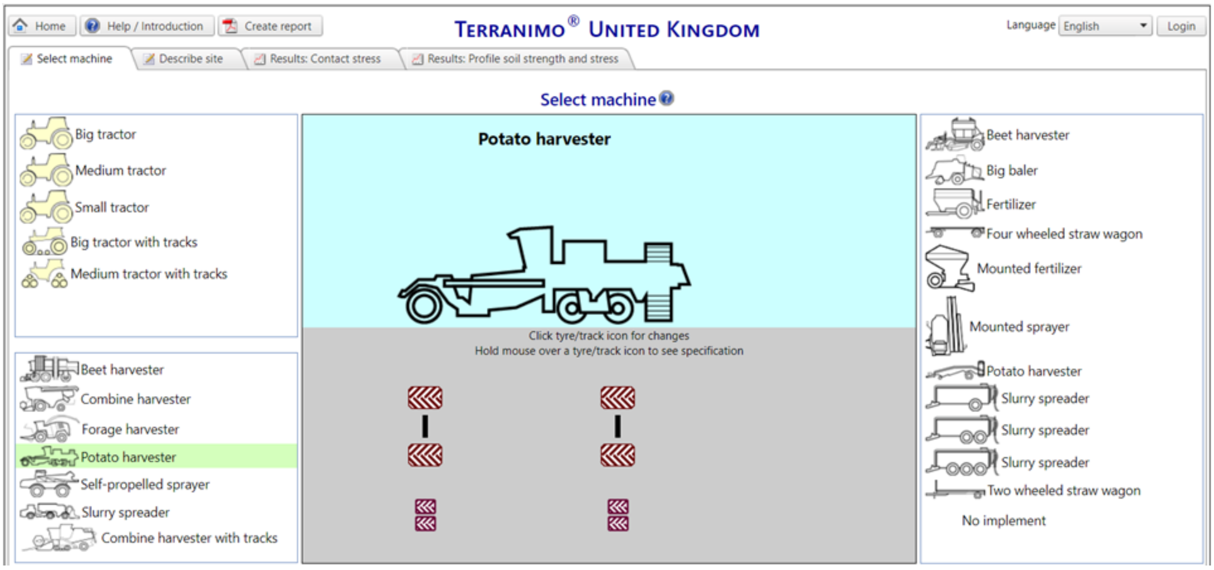


Figure 27. Addition of new machinery (e.g. tracked machines (two tractors and a combined harvester.

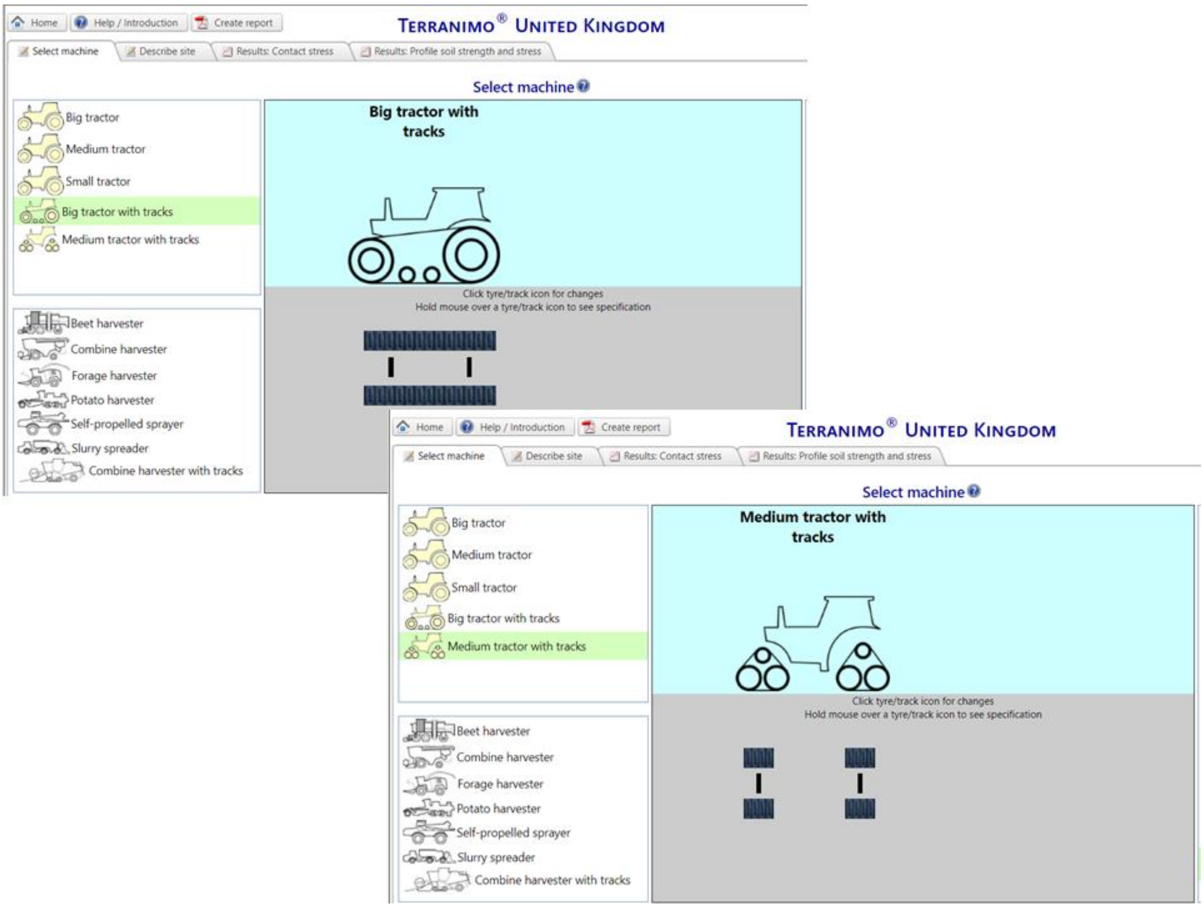
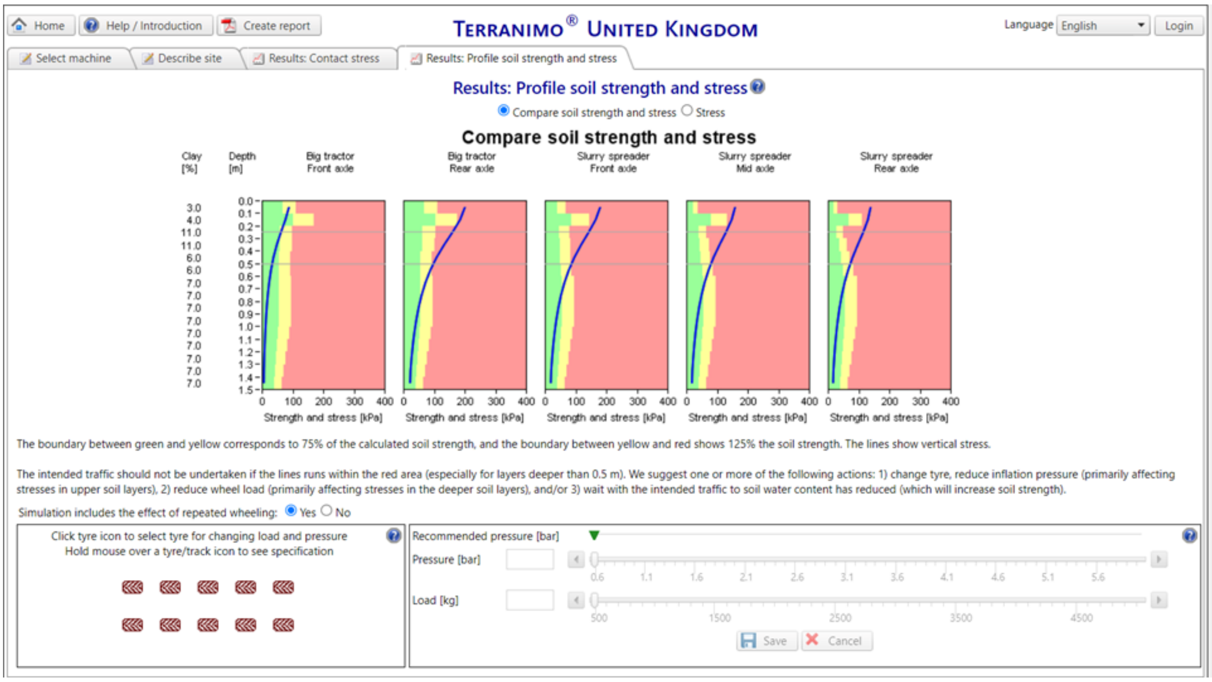


Figure 28. Assessment of the soil compaction risks that includes the impact of repeated wheeling - so the impact of each wheel passing in a given track can be considered.



The Terranimo® website was updated with several new features drawing on information on soil physical interactions with soil management, and extensive Knowledge Exchange during the development and after the release of the updates has been undertaken.

- The Terranimo model and website was adapted to allow utilisation by UK farmers.
- Selection of soil type is available for farms based in Scotland, with improvements to selection process for farms in England and Wales to be made available subject to some restriction.
- Assessment of the soil compaction risks that includes the impact of repeated wheeling was undertaken

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