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Over winter cover crops provide yield benefits for spring barley and maintain soil health in northern Europe

Jonathan Holland[a,b], Jennifer L. Brown[b], Katrin MacKenzie[c], Roy Neilson[b], Simone Piras[d], Blair M. McKenzie[b,e,*]

[a] Agri-Food & Biosciences Institute (AFBI), Newforge Lane, Belfast, BT9 5PX, UK
[b] James Hutton Institute, Dundee, DD2 5DA, UK
[c] Biomathematics and Statistics Scotland, Dundee, DD2 5DA, UK
[d] James Hutton Institute, Craigiebuckler, Aberdeen, AB15 8QH, UK
[e] Geography & Environmental Science, University of Dundee, DD1 4HN, UK

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ABSTRACT

A three-year field experiment investigated the potential yield benefits and soil effects from over winter cover crops in Scotland, U.K. Brassica composition of cover crops significantly increased the grain yield and grain nitrogen (N) concentration of the following spring barley crop. The increased yield with cover crops was outweighed by increased costs and thus without subsidy (Ecological Focus Area) payments there was decreased profitability for the following spring barley crop. Cover crop effects were mostly neutral on soil properties, but surface shear strength was significantly lower than in the stubble control. This indicates that even direct drilling of cover crops will loosen the surface soil. Cover crops varied in their effect on slug populations but in all cases slug numbers were below treatment thresholds. No cover crop effects were detected for total nematode and earthworm abundance or the total soil organic carbon concentration. This study indicates that cover crops can improve cereal production in a region with a short growing season with no negative impact on soil health or the agronomic sustainability.

1. Introduction

Cover crops may provide multiple benefits for crop production and the sustainability of agricultural systems. Over winter cover crops may be grown as part of systems to enhance biodiversity (Ditzler et al., 2021), control crop diseases (Couedel et al., 2019), sequester carbon (Lugato et al., 2014; Poeplau and Don, 2015), decrease nitrate leaching (Komainda et al., 2016), improved soil structure (Zhang and Peng, 2021) and increase yield of subsequent cash crops (Munkholm and Hansen, 2012). The potential of cover crops to maximise these benefits varies depending on soil type, location, topography, crop rotation and their management, but they will not be appropriate for all environments. For example, in northern Europe on loamy soils with little slope, cover crops may be used to decrease nutrient leaching. In these cases, it is common to plough-in the cover crops prior to winter, particularly as the cover crops are unlikely to survive until spring (Vogeler et al., 2019; Wahlstrom et al., 2021). On land with significant slope, nutrient leaching is less concerning while ploughing soil prior to winter is a major erosion risk (Davidson and Harrison, 1995) and hence land may be left with cereal stubble over winter until ploughing in spring. Similarly, there is some evidence that over winter cover crops may provide benefits under minimum and no-till systems, but be of much less use where conventional ploughing is used (McKenzie et al., 2017).

The ability of winter cover crops to provide benefits, apart from control of nutrient leaching, has received little attention in northern latitudes probably due to the restricted growing season resulting from late sowing, short day-length, and cold temperatures. Indeed, this study location was considered a challenge because of the northern latitude (56.5 °N) compared to most UK or European arable land. In this case, cover crops will need to emerge quickly and accumulate biomass before winter to be effective. While applying fertiliser to cover crops is not common it was applied here to aid rapid establishment. Bergtold et al. (2017) gives two reasons to apply fertilizer to cover crops. First to increase benefits to following cash crops but also to aid rapid establishment of cover crops so that they can suppress weeds. Chen and Weil (2011) applied fertilizer to cover crops at sowing to establish cover crops

* Corresponding author at: Geography & Environmental Science, University of Dundee, DD1 4HN, UK.
E-mail address: b.mckenzie@dundee.ac.uk (B.M. McKenzie).

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in an experiment in Maryland USA and in the second year of a 2-year experiment applied extra nitrogen in response to observed deficiency symptoms.

The aim of this study was to evaluate the effects of winter cover crops grown prior to spring barley crops that were established by conventional ploughing the soil. To avoid the risk of erosion, cover crops should not be ploughed-in until spring just prior to crop establishment. A three-year field experiment tested seven different cover crop mixtures (and a stubble control) in a typical Scottish arable field. The field was sloping and the dominant crop production in the region is plough based. Thus, the ability of the cover crops to minimise erosion to the same extent as the stubble control was an important consideration. Other considerations prompted by farmer focus groups included potential benefits to soil structure and biodiversity.

For this study to have credibility with local farmers it was deemed important to investigate cover crops with farm-scale machinery. Consequently, the objectives were: (*i*) to evaluate different cover crop treatments on the grain yield, quality and profitability of successive spring barley crops; (*ii*) to evaluate cover crop treatments for soil cover and the effects on soil stability and selected soil fauna that may respond positively to plant growth or negatively to a potential biofumigation effect.

2. Materials and methods

2.1. Site description

A three-year field experiment was established in Binn's field (56.486 °N, −3.140 °W) at the James Hutton Institute's Balruddery farm near Dundee, UK. The topsoil depths range from 30 to 40 cm with a sandy silt loam texture and are freely draining. The field has a slope of approximately 3° from west to east. The soil was formed with colluvial material and was classified as a Endostagnic Cambisol (WRB, 2015). Rainfall, temperature and other standard meteorological variables were regularly recorded at a near-by meteorological station. The long-term (1991–2020; 30-year average) autumn and winter rainfall (September to March) was 415 mm and the long-term spring and summer (April to August) rainfall was 249 mm. The monthly and seasonal rainfall was variable during the study period (Table S1). The autumn/winter rainfall is relevant for evaluating the cover crop performance, while the spring/summer rainfall is relevant for the barley crop. The mean minimum temperatures for September to March during the study period are given in Fig. S1.

2.2. Experimental design

A trial was designed with a control of stubble (including weeds and volunteers) from the previous barley (*Hordeum vulgare;* cultivar: *Concerto*) crop remaining on the soil surface and seven cover crop treatments (Table 1). For three consecutive years all treatments were replicated three times in a randomised block design. Each treatment plot was 6 m wide ×200 m long that were aligned in an east-west direction and ran up slope.

2.3. Crop management

For each of the three years, sowing and harvest followed the same pattern. Cover crops were sown in September (14/9/15, 13/9/16 and 5/9/17) soon after the harvest of a spring barley crop (2/9/16, 31/8/17 and 28/8/18) and were sown with a combination seed drill (Amazone Ltd) and fertiliser (at the rate of 30 kg N, 5.4 kg P, 19 kg K, and 4 kg S ha^{-1}) was placed with the seed. The cover crops were destroyed at the end of March each year and incorporated by conventional ploughing. Thereafter, the spring barley crop was sown in early April each year. Fertiliser was applied twice in a split with 30 % at sowing and 70 % at anthesis. The total applied rate was 110 kg N, 20 kg P, 70 kg K, and 15 kg S ha^{-1} during the whole growing season. All barley and cover crops were sown up the slope as was the barley harvest. The crop agronomy followed conventional commercial practices for the region.

Table 1
A description of the cover crop treatments[a] with the common and botanical names for each species with the corresponding composition (%) of each treatment mixture and the seed rate (kg ha^{-1}) used.

Treatment	Common name	Botanical name	Composition (%)	Seed rate (kg ha^{-1})
Jupiter Turnip	Field mustard	*Brassica rapa*	100	12
Structure Mix	Romessa Oil Radish	*Raphanus sativus*	27	25
	Winter Oats	*Avena sativa*	47	
	Rye	*Secale cereale*	13	
	Phacelia	*Phacelia tanacetifolia*	3	
	Tillage Radish	*Raphanus sativus*	10	
Defender Oil	Oil Radish	*Raphanus sativus*	100	18
Radish Mix	Romessa Oil Radish	*Raphanus sativus*	80	20
	Tillage Radish	*Raphanus sativus*	20	
Vitality Mix	Romessa Oil Radish	*Raphanus sativus*	24	25
	Winter Oats	*Avena sativa*	38	
	Berseem Clover	*Trifolium alexandrinum*	4	
	Strigosa Oats	*Avena strigosa*	12	
	Phacelia	*Phacelia tanacetifolia*	2	
	Vetch	*Vicia faba*	20	
Vetch & Rye	Vetch	*Vicia faba*	37	40
	Rye	*Secale cereale*	63	
EFA Mix	Winter Oats	*Avena sativa*	80	20
	White Mustard	*Sinapsis alba*	17.5	
	Vetch	*Vicia faba*	2.5	

[a] These cover crop mixtures were developed by Kings Crops; https://www.kingscrops.co.uk/.

2.4. Cover crop and barley crop measurements

In late March 2017 and 2018 (but not in 2016) the cover crop above-ground biomass was determined by cutting 1 m^2 from selected treatments: control, Jupiter Turnip, Structure Mix, Defender Oil and Vitality Mix. The collected plant material was dried at 60 °C to determine the dry matter (DM) biomass (kg ha^{-1}). In addition, each year in late March photographs were taken of the same five selected cover crop treatments. Three photographs were taken per treatment per block. Photographs were taken by placing a frame sub-divided by strings into 100 cm^2 squares. Image analysis software (Java ImageJ 1.51n) was used to estimate the percentage of soil covered by vegetation (including straw and dead plant material). Colour thresholding separated the pixels representing vegetation compared to the soil (bare ground).

Barley grain was harvested with a commercial scale combine. The grain quality tested for standard commercial criteria (UK Malt, 2019). The grain nitrogen content (%) was determined with a near infra-red (NIR) spectrometer (Foss Infratec™ Grain Analyser). Grain screenings were measured for >2.5 mm (retained) and <2.5 mm (screenings). Skinning (a grain quality parameter) is described as a peeling of the hull and is not desirable for malting barley (Grant et al., 2021). The skinning method followed a standard grains industry technique (Frontier Agriculture Ltd).

2.5. Soil measurements

Soil water content was measured while the cover crops were growing in the control and Jupiter Turnip, Structure Mix, Defender Oil and Vitality Mix plots in all three years. Access tubes were installed to measure soil water with a PR2 Profile probe (Delta-T Devices Ltd) at three locations in each plot. Locations were approximately the mid-point of the 200 m long plot and 50 m (west) up and (east) downslope of the mid-point. Data were collected at four depths: 0–10, 10–20, 20–30 and 30–40 cm. Measurements were taken on multiple dates through the winter months, but most frequently in March at the end of the cover crop growing period when it was possible that transpiring cover crops might dry the soil.

Undrained shear strength was measured in the control and all treatment plots using a "Pilcon" hand vane tester at three locations per plot in all three years. Locations were approximately the mid-point of the 200 m long plot and 50 m (west) up and (east) down slope of the mid-point. Root proliferation in the soil can increase soil shear strength (Donn et al., 2014). The flange size selected was 19 mm length. Data were collected by inserting the shear vane into the soil over the length of the flange from the surface (0–19 mm) depth.

Water stable aggregation (WSA) was determined by taking surface (0–10 cm) soil samples in March of 2017 and 2018. For the control and all cover crop plots, loose samples were collected near to the sites where shear vane testing was conducted. The soil was returned to the laboratory, air-dried and sieved to <8 mm to remove stones and gravel. WSA > 2 mm diameter was determined on a standard wet sieving apparatus (Eijkelkamp, Giesbeek, The Netherlands) on stone-free 4 g sub-samples of the air-dried soil. The soil was placed on a 2 mm sieve in the tray with 100 mL distilled water and sieved at 34 cycles per min for 3 min with a stroke length of 13 mm. The oven dry (105 °C) weight of soil retained on the sieve was recorded as the stable aggregate fraction. Increased water stable aggregation at the 2 mm scale has been reported in soil in which grass roots were proliferating (Tisdall and Oades, 1979; Douglas and Goss, 1982). Samples were run in triplicate for each sampling location (i.e. nine samples per plot).

The abundance of soil fauna (earthworms, slugs and nematodes) was recorded using standard methods towards the end of each March of the experiment. Earthworm populations were monitored by spade extraction of a 30 × 30 × 30 cm soil sample and hand sorting in late March in all three years. Earthworms were returned to the lab and counted. As none of the earthworms were mature adults, full species identification was not possible. Slug populations were monitored in late March each year using refuge traps in baited with chicken food mash (AHDB, 2016). Soil samples were taken (late March 2017 and 2018) to assess nematode populations using a grass plot sampler (internal diam. 2.3 cm, Eijkelkamp, Giesbeek, The Netherlands). Each composite sample consisted of approximately 20 random cores from along the length of each treatment plot to a depth of 10 cm. Soil samples were transported on ice to the laboratory and stored at 4 °C until processing. Nematodes were extracted from a 200 g subsample of soil (Wiesel et al., 2015) with a modified Baermann funnel method (Brown and Boag, 1988). After *ca.* 48 h, extracted nematodes were collected in 20 mL of water and left to settle for *ca.* 2 h. *Trichodorus*, *Pratylenchus* and spiral (*Helicotylenchus/Rotylenchus*) nematodes were identified under a binocular microscope (Wild) at x40 and enumerated along with an estimate of total nematode abundance. Finally, before ploughing to destroy the cover crop, soil samples were collected to determine the total soil organic carbon (C) and nitrogen (N) concentration which were determined using an Elemental Analyser (Thermo Flash EA 1112, Thermo Fisher Scientific).

2.6. Gross margin analysis

Most costs and prices for calculating the profitability of the spring barley crops and the cover crop treatments were taken from The Farm Management Handbook 2019/2020 (SAC Consulting, 2019). For appreciating the additional costs of establishing the cover crops, besides seed costs also planting costs (one pass cultivation with own machinery/by a contractor) were subtracted from the gross margins. The cost of cover crop seed and cultivation with own machinery (£16 ha^{-1}) were directly calculated from our own data. Output prices were based on values for grain yield and straw and are anticipated sales prices; variable costs are based on the projected values for 2019. In addition, the inclusion of a subsidy payment (Ecological Focus Area, EFA) was evaluated in the gross margin analysis (Rural Payments, 2020), except for the control treatment.

2.7. Statistics

Analysis of variance was used to test for differences between variables where the data were balanced. For unbalanced variables, residual maximum likelihood (REML) was used. The crop cover mixtures were treated as a fixed effect, while block, plot within blocks, sample point location and year were treated as random effects. A regression of grain yield (and grain quality variables) as a response variable against the percentage brassica composition in each mixture was undertaken. Analyses were performed using Genstat Version 18.1. (VSN International, 2015).

3. Results

3.1. Cover crop effects on barley grain yield and grain quality

Following the cover crops, the barley grain yield was measured in 2016, 2017 and 2018. Significant cover crop treatment effects ($P = 0.008$) compared with the control were detected on the three-year mean data (Fig. 1a). There was a positive linear effect of the percentage brassica composition (see Fig. 1) of the cover crop mixtures on grain yield ($P < 0.001$). There was a weaker but still strongly significant ($P < 0.001$) negative linear effect of percentage grass composition. This correlation includes the barley stubble control as 100 % grass. Two treatments with 100 % brassica composition (Radish Mix, Defender Oil) had significantly ($P < 0.05$) greater yield than all the other cover crop treatments. In contrast, three treatments had the significantly ($P < 0.05$) lowest grain yield over the course of the experiment (control, Vetch & Rye, EFA Mix). In addition, there were significant year effects ($P < 0.001$); overall mean yield in 2017 (8.15 t ha^{-1}) was the greatest, followed by 2016 (7.77 t ha^{-1}) and the least yield (6.38 t ha^{-1}) was in 2018.

Barley grain quality was determined for each year of the study (2016, 2017 and 2018). Cover crop had a significantly effect ($P = 0.035$) on grain nitrogen (N %) concentration (Fig. 1b). In accordance with the grain yield (Fig. 1a) a highly significant linear positive increase ($P < 0.001$) was detected for the percentage brassica composition on grain N %. The cover crop treatment × year interactions were not significant ($P > 0.05$) for both yield and grain N%. Cover crop effects were observed on the percentage of small grains (retained > 2.5 mm and screenings < 2.5 mm), but there was no significant effect found for the 1000 grain weight or for the percentage skinned grain (Table 2). For each grain quality variable there was a highly significant effect ($P < 0.001$) between years (Table 2), but no significant cover crop treatment × year interaction effects were detected. For screenings and skinned, 2018 values were significantly different from both 2016 and 2017.

3.2. The profitability of including cover crops before a spring barley crop

The profitability of the cover crops was evaluated by calculating crop gross margins (Table 3) based on the mean (three year) barley grain yield (Fig. 1). The financial value of yield (£ ha^{-1}) for several cover crop treatments was greater than for the control, however due to the greater variable costs, the gross margin for the control treatment was greater

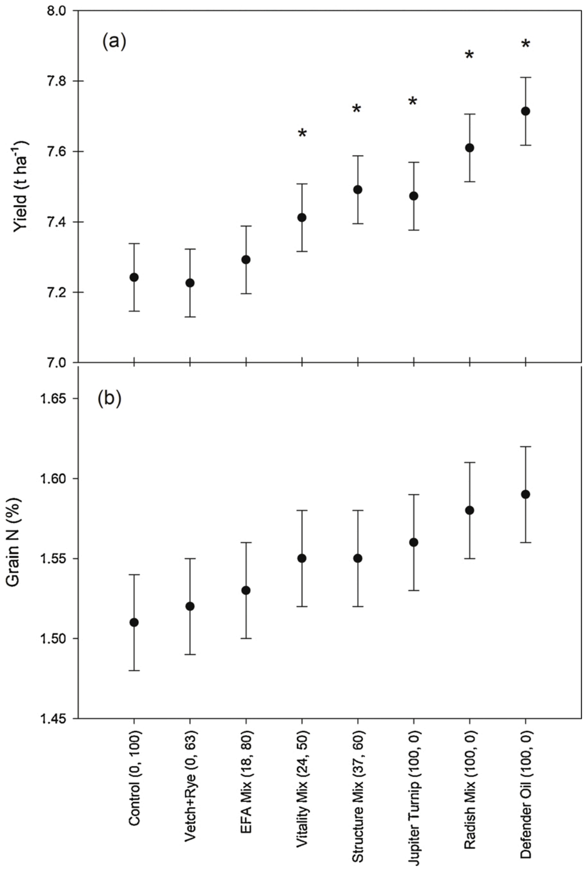

Fig. 1. The effect of different cover crop treatments (according to percentage brassica composition first and percentage grass composition second) given in brackets: Control, Vetch & Rye, EFA Mix, Vitality Mix, Structure Mix, Jupiter Turnip, Radish Mix and Defender Oil) on (a) barley grain yield (t ha^{-1}) and (b) grain nitrogen (%) based on the three year mean (●) with bars representing the standard error. * indicates where treatments are significantly (P < 0.05) greater than the control.

Table 2
Cover crop and year effects on mean barley grain quality variables: 1000 grain weight (g), retained > 2.5 mm (%), screenings < 2.25 mm (%), skinned (%).

Treatment	1000 grain weight (g)	Retained > 2.5 mm (%)	Screenings < 2.25 mm (%)	Skinned (%)
Control	66.1	96.2	1.28	3.9
Jupiter Turnip	66.2	95.8	1.57	5.5
Structure Mix	66.5	95.6	1.87	5.1
Defender Oil	66.5	96.3	1.42	5.0
Radish Mix	66.6	95.4	1.76	4.3
Vitality Mix	66.3	96.0	1.57	5.0
Vetch & Rye	66.0	95.8	1.58	4.4
EFA Mix	66.1	96.7	1.17	4.2
Treatment - SED[a]	0.22	0.38	0.2	1.2
2016	65.6	95.7	1.6	3.7
2017	67.0	94.4	2.0	9.9
2018	66.3	97.8	0.9	0.4
Year - SED[a]	0.14	0.23	0.12	NA
Treatment[b]	0.075	0.032	0.017	0.615
Year[b]	<0.001	<0.001	<0.001	<0.001
Interaction[b]	NS	NS	NS	NS

[a] Standard errors of differences of means.
[b] P value; NS = not significant where P > 0.05.

Table 3
The spring barley crop output (£ ha^{-1}), total variable costs (£ ha^{-1}), gross margin (£ ha^{-1}) and comparisons between the control and the cover crop treatments.[a]

Treatment	Output (£ ha^{-1})	Total variable costs[b] (£ ha^{-1})	Gross margin (£ ha^{-1})	Control – cover crop gross margin[c] (£ ha^{-1})	Control – cover crop gross margin with EFA[d] (£ ha^{-1})
Control	1422	338	1084	–	–
Jupiter Turnip	1468	381	1087	3	150
Structure Mix	1471	402	1069	−15	133
Defender Oil	1515	429	1086	2	150
Radish Mix	1494	417	1078	−6	141
Vitality Mix	1456	397	1059	−25	122
Vetch & Rye	1419	398	1021	−63	85
EFA Mix	1432	390	1042	−43	105

[a] Output based the mean three grain yield values given in Fig. 1.
[b] The total variable costs for barley and cover crops include all seed and management costs. No cover crop costs for the control treatment.
[c] The control gross margin (inclusive of machinery costs for both barley and cover crops) minus the cover crop gross margin.
[d] EFA payment is added to the gross margin for the cover crop treatments. The 2019 flat rate for region 1 (https://www.ruralpayments.org/) was £147.71 ha^{-1}; based on the exchange rate on 9 June 2019 (https://www.bankofengland.co.uk/).

than most cover crop treatments except for the Jupiter Turnip and the Defender Oil treatments (Table 3). With inclusion of the EFA payment (£147.71 ha^{-1}) all cover crop treatments had a significantly greater gross margin than the control (without any subsidy payment), with the greatest gross margin of >£150 ha^{-1} for the Jupiter Turnip treatment.

3.3. *Cover crop effects on biomass and ground vegetation cover*

The overall (based on 2017 and 2018) dry matter (DM) was significantly (P < 0.001) greater for all (except the Structure Mix) the cover crop treatments than the control (Table 4). The Jupiter Turnip treatment had around three times greater biomass than the other treatments. Likewise, there were highly significant (P < 0.001) treatment and year effects in the percentage of vegetation cover (Table 4). Overall, the Jupiter Turnip treatment had the greatest cover which was significantly greater than the stubble control. In comparison the vegetative cover for the other treatments (Structure mix, Defender Oil and Vitality mix) (Table 4) was less than the stubble control.

Table 4
Cover crop treatment[a] effects on the overall mean dry matter (DM) biomass and vegetation cover (VC) (%) in each year of the experiment.

Treatment	Dry matter (kg ha^{-1})	Vegetation cover (%)
Control	0.14	51
Jupiter Turnip	0.64	56
Structure Mix	0.14	41
Defender Oil	0.22	43
Vitality Mix	0.25	40
SED - Cover crop[b]	0.05	3.4
SED - Year[b]	NA	2.5
P value - Cover crop	<0.001	<0.001
P value – Year	NA	<0.001

[a] The three cover crop treatments not included were: Radish Mix, Vetch & Rye and EFA Mix.
[b] Standard errors of difference.

3.4. Cover crop effects on soil properties and soil fauna

Cover crop treatment effects were tested on selected soil physical and chemical properties and soil faunal abundance (Table 5). There were no significant effects on the soil water content at 0–10 cm depth (Table 5) or at the other measured depths (data not shown). Cover crop effects were detected on the shear vane strength at the soil surface (0–19 mm) (Table 5). At the surface the stubble control treatment had significantly greater shear strength than all cover crop treatments. No significant cover crop effects were detected on water stable aggregates and likewise there was no effect on earthworm populations (Table 5). While there were no treatment effects on total numbers of nematodes nor were there differences in the *Trichodorus*, *Pratylenchus* or spiral nematode abundance, however a year effect ($P < 0.05$) was evident for spiral nematodes (data not shown). Cover crop treatments had a significant effect on slug numbers (Table 5). The Vitality mix had the greatest number of slugs, followed by the control treatment with the smallest number detected in the Structure mix, but these treatment differences were not significant ($P > 0.05$). Total soil organic C (%) content was not significantly different between the cover crop treatments (Table 5) nor were there any total soil N effects (data not shown).

4. Discussion

4.1. Evaluation of the benefits of cover crops for northern European agronomy

The yield benefit on spring barley was increased according to the percentage brassica composition in the cover crop mixture (Fig. 1a). Analysis of the three year mean data showed that all cover crop treatments with >20 % brassica content (see Table 1) significantly increased grain yield compared to the control. The only two cover crop treatments that did not lead to greater grain yield were the Vetch & Rye and the EFA Mix despite like other cover crops receiving fertilizer at establishment. The yield gain from Defender Oil treatment was 0.47 t ha^{-1} (Fig. 1a) greater than the control; this increased the economic output, by £150 ha^{-1} when the EFA payment was included (Table 3).

Previous studies have reported that cover crops can provide a wide range of benefits to the yield of a subsequent crop, including soil erosion control, soil fertility/crop nutrition, less crop disease, reduced N leaching and weed suppression. The effects of cover crops on soil fauna for a following crop are complex with multiple soil-plant interactions. For example biofumigation effects may suppress disease, but also harm beneficial organisms (Tisdall et al., 2012). The increased grain yield from the cover crops with the highest brassica composition was probably due to ability of the cover crops with brassica to minimise NO_3^- leaching and maintain greater residual soil N. Sapkota et al. (2012) reported greater root growth in radish cover crops which decreased NO_3^- leaching. Cooper et al. (2017) found that over winter radish cover crops increase net soil N accumulation. Therefore, it is possible that the cover crops with brassica have stored additional soil residual mineral N, from the above-ground material and their roots systems, that is then available for the subsequent spring barley crop. If this is the case, some of the extra N may have derived from the fertilizer applied to the cover crop at sowing in a manner suggested by Bergtold et al. (2017). In contrast cover crops with rye can decrease soil mineral N (White et al., 2016). Similar benefits from radish containing cover crops on spring barley yield have been observed in elsewhere in Northern Europe (Toom et al., 2019).The cover crops were sensitive to the winter temperatures which differed greatly between years (Fig. S1). Consequently, the lowest percentage vegetation cover was observed in 2018 (Table 4) and corresponded with the coldest temperatures (Fig. S1). Likewise, the grain yield differed significantly between years due to season growing conditions. Specifically, there were large differences in rainfall. The lower spring/summer rainfall (Table S1) and warmer temperatures in 2018 resulted in the smallest grain yield. In comparison, the barley growing conditions in 2016 and 2017 were more favourable and there was significantly greater grain yield. Thus, year effects were much larger than the cover crop effects and there was no indication of any benefits of cover crops increasing with year. Strong inter year and rainfall effects are typical for spring barley in Scotland and have been recently reported (Cammarano et al., 2019). Subsidy (EFA) payments are important to ensure that cover crops have increased profitability compared to the control treatment (Table 3). Without the EFA payments there is little financial incentive for farmers to include cover crops in their crop rotations, although our analysis showed that on average the greater barley yield can compensate the additional costs for at least two of the cover crop treatments (Jupiter Turnip and Defender Oil).

4.2. Evaluation of cover crops effects on soils

Cover crops had variable effects on soil properties and soil fauna. There was no significant effect on soil water content or aggregate stability (Table 5). In contrast, Basche et al. (2016) found that winter rye cover crops increased soil water storage. Moreover, research from Denmark has reported a significant interaction between tillage and cover crops that improved soil aggregate friability (Abdollahi and Munkholm, 2014). This suggests that cover crops with limited opportunity to vigorously establish were neutral in terms of important soil physical condition immediately prior to the establishment of the spring barley crop. Over the three years of the study there were large differences in the amount of rainfall received (Table S1), but this did not correspond with any negative effect on soil water content. In the first year the very wet winter months (2015/16) (Table S1) corresponded with no significant effect in soil water content or for the other soil properties. All cover crop treatments had significantly lower surface shear vane strength than the control treatment of intact barley stubble (Table 5). This suggests that even the minimal soil disturbance needed to

Table 5
The effects of cover crop treatments on soil properties (soil water content at 10 cm, surface shear vane strength and water stable aggregates <2 mm), soil biology (number of nematodes, earthworms and slugs) and total soil organic carbon (%) content.[a]

Treatment	Soil water content (cm^3 cm^{-3})	Surface shear vane (kPa)	WSA >2 mm	Nematode[b] no.	Earthworm[b] no.	Slug[b] no.	C (%)
Control	0.214	26.9	0.63	915	5.6	0.38	3.4
Jupiter Turnip	0.205	20.7	0.64	2322	4.0	0.14	3.5
Structure Mix	0.210	19.6	0.59	1597	1.67	0.10	3.4
Defender Oil	0.188	20.6	0.65	1657	4.47	0.30	3.4
Radish Mix	–	19.6	0.60	1752	–	–	3.5
Vitality Mix	0.180	22.9	0.60	1182	3.4	0.44	3.4
Vetch & Rye	–	18.9	0.64	1807	–	–	3.4
EFA Mix	–	19.1	0.63	1448	–	–	3.5
SED	0.015	1.0	0.030	436	2.12	0.14	0.1
P value	0.31	<0.001	0.296	0.10	0.302	0.038	0.07

[a] Mean values are presented from two or three years of the experiment.
[b] Total nematode abundance (200 g^{-1} soil), earthworm abundance 30 × 30 × 30 cm, slug no. per bait trap.

establish cover crops has weakened the surface soil. Any of the options to maintain (barley stubble) or establish (cover crops) soil cover will be preferable for erosion control than the common practice of leaving bare ploughed soil over winter (Misra and Rose, 1995). The detection of soil faunal effects was mixed with selected cover crop treatments (i.e. Jupiter Turnip and Structure Mix) significantly reducing the number of slugs compared to the control, but there was a significant increase in slug number for the Vitality Mix treatment (Table 5). This indicates the importance in the choice of cover crop treatment for the management of slugs which can be a serious crop pest, although in plough based systems slug numbers may be decreased by soil inversion (Rowen et al., 2020). In contrast, there were no cover crop effects on the numbers of nematodes or earthworms (Table 5). Thus, there is no indication of a biofumigation effect for these treatments on the soil fauna. Earthworm and nematode samplings were done in late March, but prior to destruction and incorporation of the above ground biomass with ploughing. It is possible that such incorporation may release biofumigants from the damaged plant tissue (both roots and above ground). Due to the length of this study (three years) and as it was a plough-based system cover crops did not increase the soil organic carbon content (%) (Table 5). Chenu et al. (2019) suggest that sandy soils, as in this work, are less able to respond to management by increasing carbon stocks than soils with more clay. However, long-term (>16 years) use of ryegrass cover crops can increase in soil organic carbon stocks even in sandy soils (Poeplau et al., 2015).

Jian et al. (2020) developed a tool (cover crop calculator) to estimate cover crop effects on subsequent cash crop yield and on soil health. Applying the results from this study (Tables 1, 2, 4 and 5) the tool from Jian et al. estimates that a cover crop including brassicas had a yield benefit of 3.9 % for the cash (barley) crop, while a cover crop with grasses estimates a yield penalty of 1.1 %. This estimate is in general agreement with the yield responses observed in this study, although the Defender Oil treatment had an even greater yield benefit of 6.5 % (Fig. 1a). The tool was not helpful in estimating most soil effects and this indicates there is scope to further validate the cover crop calculator where cover crop growth during winter is limited. Nevertheless, the soil effects observed (Table 5) in this study indicate that soil health was not significantly decreased from the cover crops and that soil health condition was at least maintained. Further work is required to better attribute the mechanisms for the response of field crops to cover crops and to better understand the magnitude of cover crop effects on soils and on reducing NO_3^- leaching. Research is also required on the interaction of cover crops with different tillage systems (e.g. especially no tillage) and to investigate whether any significant soil C storage benefit can be derived over the longer term.

5. Conclusions

In a northern European environment, winter cover crops can provide vegetation cover to reduce the risk of erosion and increase yield of a subsequent spring barley crop. In this study, even under challenging conditions, over winter cover crops could be established and those with a large brassica component have agronomically important yield benefits for the subsequent cereal crop grown under ploughed methods. Evaluation of the different species within the cover crops indicated that barley grain yield increased according to the percentage brassica composition in the cover crop and in particular the oil radish treatment provided the greatest grain yield for the following crop. However with time constrained to three years the environmental benefits in terms of erosion control, soil carbon accumulation and improved soil biota were limited. With the EFA payment all gross margins of the cover crops were greater than the control treatment, but without the EFA payment there is little benefit from cover crops for profitability. The financial benefits of any increased yield were offset by the cost of establishing the cover crops. Thus, EFA or a similar subsidy is needed to provide financial incentives for farmers to reduce the cost of growing cover crops.

CRediT authorship contribution statement

All authors contributed to the writing, provided critical feedback, and gave approval for the manuscript. **Jonathan Holland** coordinated the writing and delivered the agronomy. **Jennifer L. Brown** delivered the image analysis. **Katrin MacKenzie** delivered the statistical analysis. **Roy Neilson** delivered the nematode analysis. **Simone Piras** delivered the economic assessment. **Blair M. McKenzie** planned and designed the experiment, secured funding, and delivered the soil physics and macrofaunal assessment.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.eja.2021.126363.

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