Plant Soil
https://doi.org/10.1007/s11104-026-08892-y

RESEARCH ARTICLE

Influence of field beans (*Vicia faba L.)* on yield and environmental footprint of following spring barley (*Hordeum vulgare L.*) crops

Umut Kartal · Colm Duffy · Sophie Saget · Frances Sandison · Andrew Christie · Cathy Hawes · Becky Howard · Roger Vickers · Dimitrios Savvas · David Styles · Pietro P. M. Iannetta

Received: 15 December 2025 / Accepted: 14 July 2026

Abstract
Background and Aims The urgent need to reduce greenhouse gas emissions has increased interest in legume-based cropping systems. Among the various crop-legume species available, the cool-season species *Vicia faba* L. (cv. minor; field beans) has attracted significant interest. Assessment of the environmental impact reduction of field beans in a crop-sequence (rotation) is understudied.
Methods Data from a long term (2009–2023) field bean experimental platform (the Centre for Sustainable Cropping, CSC; James Hutton Institute, Scotland, UK) were analysed using attributional life cycle assessment (aLCA). This focused on elaborating the impacts of a spring field bean to spring barley (*Hordeum vulgare* L.) cropping sequence compared with a spring barley to spring barley cropping sequence.
Results Field beans decreased the environmental impact of spring barley production in four of the five two-year crop-sequence periods, with mean impact reductions of approximately 25% across sequences. Spring barley grain yields tended to increase following field beans under drought conditions (2022). A combined index analysis indicated that humidity, maximum temperature, and previous field bean yields were the strongest determinants of spring barley production.
Conclusions The integration of field beans to cereal-dominated rotations may be of interest to major industries who seek to improve value chain

Responsible Editor: Carla S. Santos.

U. Kartal · F. Sandison
Information and Computational Sciences Department, The James Hutton Institute, Aberdeen, UK
e-mail: ukartal05@gmail.com

U. Kartal (✉) · A. Christie · C. Hawes · P. P. M. Iannetta
Ecological Sciences Department, The James Hutton Institute, Dundee DD2 5DA, Scotland, UK

U. Kartal · C. Duffy · S. Saget · D. Styles
Ryan Institute, University of Galway, University Road, Galway H91 REW4, Ireland

B. Howard · R. Vickers
Processors & Growers Research Organisation (PGRO), Peterborough PE8 6HJ, UK

D. Savvas
Lab. Vegetable Production, Dept.CropSci, Agricultural University of Athens, Athens, Greece

P. P. M. Iannetta
Centro de Biotecnologia e Química Fina (CBFQ), Laboratório Associado, Escola Superior de Biotecnologia, Universidade Católica Portuguesa, Porto, Portugal

Published online: 20 August 2026

sustainability, whilst ensuring crop-sequence yields are climate-impact resilient.

Highlights

- Field beans reduced synthetic nitrogen fertiliser use by up to 20% (22 kg N ha^{-1}) for following spring barley crop.
- Cropping spring field beans before spring barley significantly reduced LCA-based environmental impacts.
- An index was developed using climate data and bean yields to estimate the yield of spring barley crops following beans.
- Following field beans (vs spring barley), increased average barley yields by 1.2 t ha^{-1}.

Keywords *Vicia faba* · *Hordeum vulgare* · Crop rotation · Life cycle assessment · Environmental impact

Introduction

The United Kingdom is the third largest cereal producer in the EU, with 28% of its barley (Hordeum vulgare L.) area in Scotland (NFUS 2018). Spring barley is the predominant cereal crop in Scotland, covering an estimated 134,744 ha and accounting for over 58% of Scottish arable farmland used for cereal production (Scottish Government, 2019). The majority serves as a feed source for sectors of major socioeconomic importance – brewing/distilling and livestock production (Newton et al. 2011). However, Scottish barley production, like most cereal-dominated systems in the industrialised global north, faces increasing pressure to improve resource-use efficiency and reduce environmental impacts, particularly those associated with synthetic nitrogen (N) fertiliser manufacture and use. These impacts include direct and indirect nitrous oxide (N_2O) emissions from fertilised soils, ammonia (NH_3) volatilisation contributing to acidification and eutrophication, fossil energy consumption in fertiliser manufacture, and nitrate leaching to freshwater bodies (Frischknecht et al. 2016). Additionally, co-products from brewing and distilling are increasingly routed to bioenergy production, reinforcing feed-protein import dependency and associated land-use pressures in exporting regions (Duffy et al. 2023).

Re-introducing grain legumes (Fabaceae) into cereal rotations offers a nature-based strategy to address multiple impact categories simultaneously (Altieri and Nicholls 2020). The mechanism operates through several linked pathways: (i) biological nitrogen fixation (BNF) by the legume–rhizobium symbiosis reduces or eliminates the need for synthetic N fertiliser during the legume phase and provides residual N for the following cereal crop, thereby reducing N_2O emissions from both fertiliser manufacture and field application (Köpke and Nemecek 2010; Jensen et al. 2010; Graham and Vance 2003; Rochester et al. 1998); (ii) reduced N inputs lower the risk of nitrate leaching and ammonia volatilisation, decreasing freshwater eutrophication and terrestrial acidification potentials; (iii) lower fertiliser demand reduces upstream fossil energy consumption; and (iv) the break-crop effect can suppress cereal-specific diseases and weeds, reducing pesticide requirements (Angus et al. 2015; Gan et al. 2015; Weisberger et al. 2019). These pathways are directly quantifiable within an attributional life cycle assessment (aLCA) framework.

Among the cool-season grain legumes, spring field bean (*Vicia faba* L.) has attracted particular interest due to its high BNF capacity, adaptation to temperate climates, and suitability as a break crop in cereal-dominated rotations (Karkanis et al. 2018; Stagnari et al. 2017; Vasconcelos et al. 2020). Meta-analyses indicate that including legumes in rotations can enhance subsequent cereal yields by approximately 20% globally, with greater advantages in low-input systems (Zhao et al. 2022), and reduce endogenous N requirements by up to 50% (Costa et al. 2021; Barbieri et al. 2017; Davis et al. 2012; Shah et al. 2021). Legume-inclusive rotations have also been shown to decrease global warming potential by 6–11% compared to conventional cereal monocultures (Hayer et al. 2010; Beillouin et al. 2021). Despite these benefits, legumes occupy only about 1.5% of European arable land (Iannetta et al. 2021), and field-scale evidence quantifying the environmental benefits of specific legume–cereal sequences using LCA remains limited (Balázs et al. 2021).

Accurately assessing the sustainability of legume-inclusive rotations requires considering crop sequences, nutrient cycling effects, and multiple functional units to capture the multifunctional outputs of rotations (Costa et al. 2020). By conducting an attributional life cycle assessment (aLCA) we aim to quantify the environmental impacts of a spring field bean into spring barley crop sequence in Scotland, and specifically to test two key hypotheses: incorporating spring field beans before spring barley would both (i) increase spring barley yields, and; (ii) decrease the environmental impact of the spring barley grain produced. Through this study, we also aim at contributing to the broader conversation on legume-inclusion for sustainable agricultural practices, and their potential to address pressing global challenges.

Methods

In this study, we utilised LCA methodology to comprehensively evaluate the environmental impacts of incorporating field beans into spring barley crop sequences.

Attributional LCA

LCA is a rigorous and systematic method utilised to evaluate the environmental impacts associated with all the stages of a product's life cycle, from cradle to grave. This methodology aids in identifying significant contributors to environmental burdens across different life cycle stages, reveals potential shifts in impact from one category to another, and facilitates comparisons among products that deliver equivalent functional value (Curran 2015; Goedkoop et al. 2016, 2008; ISO 14040:2006; Finnveden et al. 2009). As stipulated by ISO 14044:2006, an LCA must comprehensively cover four critical phases: goal and scope definition, inventory analysis, impact assessment, and results interpretation (ISO 2006).

Goal and scope

In this research, we performed a comparative aLCA of spring barley produced in a two-crop sequence of either [spring barley-to-spring barley] (SB–SB) or [spring field bean-to-spring barley] (FB–SB). The analysis covered five crop-sequence periods: 2017–2018, 2018–2019, 2019–2020, 2020–2021, and 2021–2022, where the first year denotes the preceding crop and the second the spring barley harvest year. For each year, one FB–SB observation was obtained from the CSC (conventional half), and two to five SB–SB observations from adjacent commercial fields (Table 2); the mean SB–SB value per year was used for paired comparisons ($n = 5$ paired observations). No crop-sequence periods were excluded. The analysis was conducted using openLCA software, version 2.1.0.

The functional unit defined for this LCA was the production of one kg of spring barley, harvested and ready for distribution. This unit facilitates the direct comparison of environmental impacts across different agricultural methods by standardizing the output measure. By focusing on this functional unit, the study ensures that the comparisons of environmental burdens are based on a consistent and equitable basis, thereby allowing for accurate and relevant environmental assessments.

System boundary

The LCA was "cradle to farm gate", i.e. the stages assessed ranged from raw material extraction to spring barley harvest (Fig. 1).

Inventory analysis

The Centre for Sustainable Cropping (CSC) (Dundee, Scotland UK) provided the foreground data for this study, which included details on all applications of fertiliser and pesticides and field operations. Background data about the environmental effects of these inputs and activities were obtained from the Ecoinvent v3.9 database (Wernet et al. 2016), which offers a wealth of information on material production and process burdens at different life cycle stages.

The Centre for Sustainable Cropping (CSC) at Balruddery Farm, Scotland, adopts a whole-systems framework to test the long-term effects of integrated or regenerative crop management for achieving multiple co-benefits and optimising trade-offs, contributing to economic and environmental sustainability (Hawes et al 2019; Roberts et al. 2023). The CSC was established in 2009 as a split field experiment comparing an integrated cropping system against standard commercial practice for each of six crops over multiple crop rotations (Fig. 2). A full site description is given in Freitag et al (2018) and Hawes et al (2018). Briefly, the integrated system combines reduced tillage,

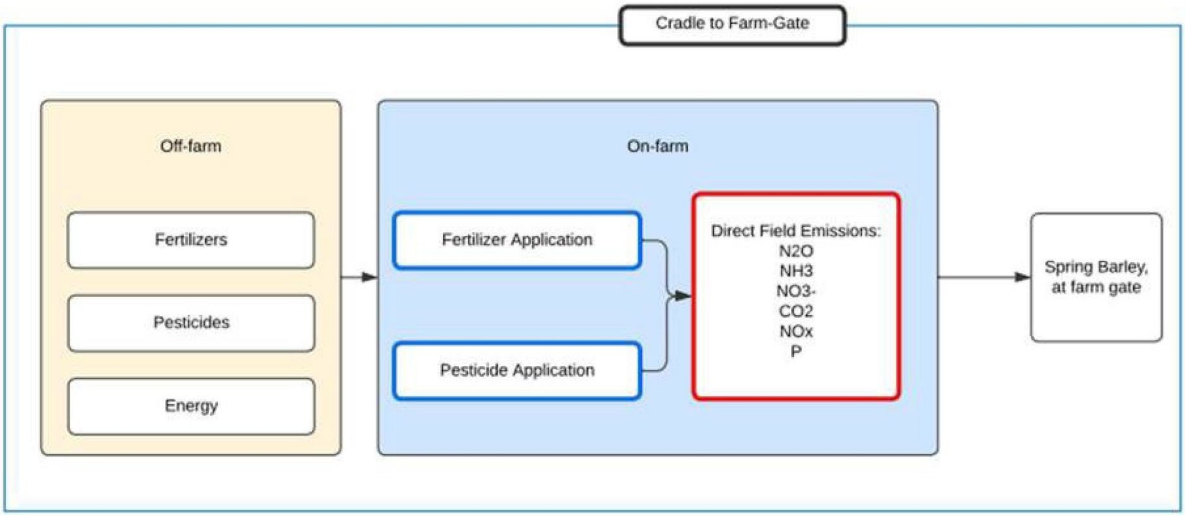

Fig. 1 System Boundary for the Cradle-to-Farm-Gate LCA

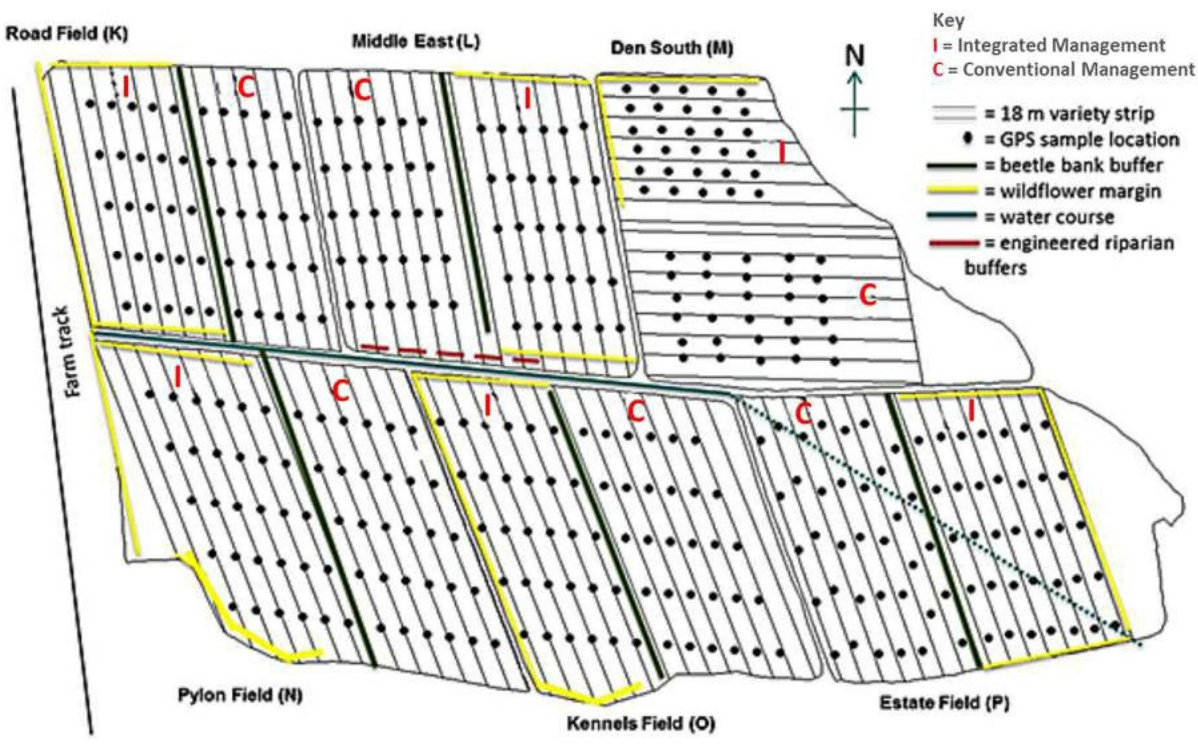

Fig. 2 Centre for Sustainable Cropping split field experimental design showing landscape features on 'conventional' (C) and 'integrated' (I) field-halves. Each crop is present in one field each year and the rotation of crops moves clockwise around the 6 fields with potato in Road field at the start of each rotation, followed by winter wheat (Pylon), winter barley (Kennels), winter oilseed (Estate), field beans (Den South) and spring barley (Middle East)

organic matter amendments, cover and companion cropping, weed, pest and disease threshold monitoring, targeted crop protection applications and nutrient budgeting to reduce reliance on chemical interventions by promoting soil health, plant fitness and biodiversity. Overlaid on each of the two cropping systems treatments are 18–36 m wide × 200 m long strips sown with 3–6 different commercially available cultivars of each crop to test varietal responses to the change in management practices. Replication is year-on-year, but large field sizes allow commercially realistic estimates of costs and benefits. Long-term trends in systems indicators (soil properties, biodiversity, crop yield and quality and financial margins) are used to review how well the sustainability objectives are met and guide further improvements in system design.

The crop rotation at the CSC includes 'potato, winter wheat, winter barley, winter oilseed, field beans, and spring barley'. These crops were selected to maintain relevance to the regional socioeconomic paradigm and so represent the most commonly grown and commercially relevant crops for the region (Angus), in which the CSC is based; and which form the basis of majority of the crop research at the James Hutton Institute (JHI). The complete cropping history for each field from 2011 to 2021 can be seen in Table 1.

A full description of the CSC platform, its treatments, and measures can be found at: https://csc.hutton.ac.uk, (see also: Freitag et al. 2018; Hawes et al. 2019, Hawes et al. 2018).

Since the CSC data lacked an internal control treatment (i.e. no [spring barley to spring barley] crop sequence) data from fields adjacent to the CSC which incorporated spring barley-to-spring barley for the same years was accounted. The position of these fields relative to the CSC is illustrated in Figure 3. This comparison represents a contrast between cropping systems under real farming conditions, rather than a randomised controlled experiment. Consequently, differences between FB–SB and SB–SB may partly reflect site-specific factors in addition to the preceding-crop effect (see Section 4).

Commercial field data from CSC adjacent fields is available from 2018 to 2022, presenting data to compare for 5 years, and from across several fields (Binns, Hutchens, Mains of Fowlis, Quarry, South America, Cottages) for each crop-year (Table 2).

The CSC at Balruddery Farm has 360 permanent GPS (global positioning system) locations across the site for monitoring key arable systems indicators throughout each growing season. This extensive monitoring is important for understanding the environmental and agronomic impacts of different cropping systems.

Crop management

Conventional practices focus on maintaining tried and tested methodologies that rely heavily on standard agricultural inputs and techniques. The conventional side of the CSC is representative of most common

Table 1 Crop rotations for each CSC field 2011–2022. P, potato; SFB, spring field bean; SB, spring barley; SOSR, spring oilseed rape; WB, winter barley; WOSR, winter oilseed rape; WW, winter wheat

Year	Field Name					
	Road	**Middle East**	**Den South**	**Pylon**	**Kennels**	**Estate**
2011	P	SB	SFB	WB	WOSR	WW
2012	WW	P	SB	WOSR	WB	SFB
2013	WOSR	WW	P	WB	SFB	SB
2014	SB	SFB	WW	WOSR	WB	P
2015	WOSR	SB	SFB	WB	P	WW
2016	WB	WOSR	SB	P	WW	SFB
2017	P	SB	SFB	WW	WB	WOSR
2018	WW	P	SB	WB	WOSR	SFB
2019	WB	WW	P	WOSR	SFB	SB
2020	SOSR	WB	WW	SFB	SB	P
2021	SFB	WOSR	WB	SB	P	WW
2022	SB	SFB	WOSR	P	WW	WB

Table 2 Available data from commercially cultivated spring barley (SB) fields (X)

Year	Field Code (name)					
	SB-1	**SB-2**	**SB-3**	**SB-4**	**SB-5**	**SB-6**
	Binns	Hutchens	Mains of Fowlis	Quarry	South America	Cottages
2018	X					
2019					X	
2020			X		X	
2021	X	X	X	X		
2022	X	X	X	X		X

Field names (Fig. 3) have been converted to SB-1 to SB-6

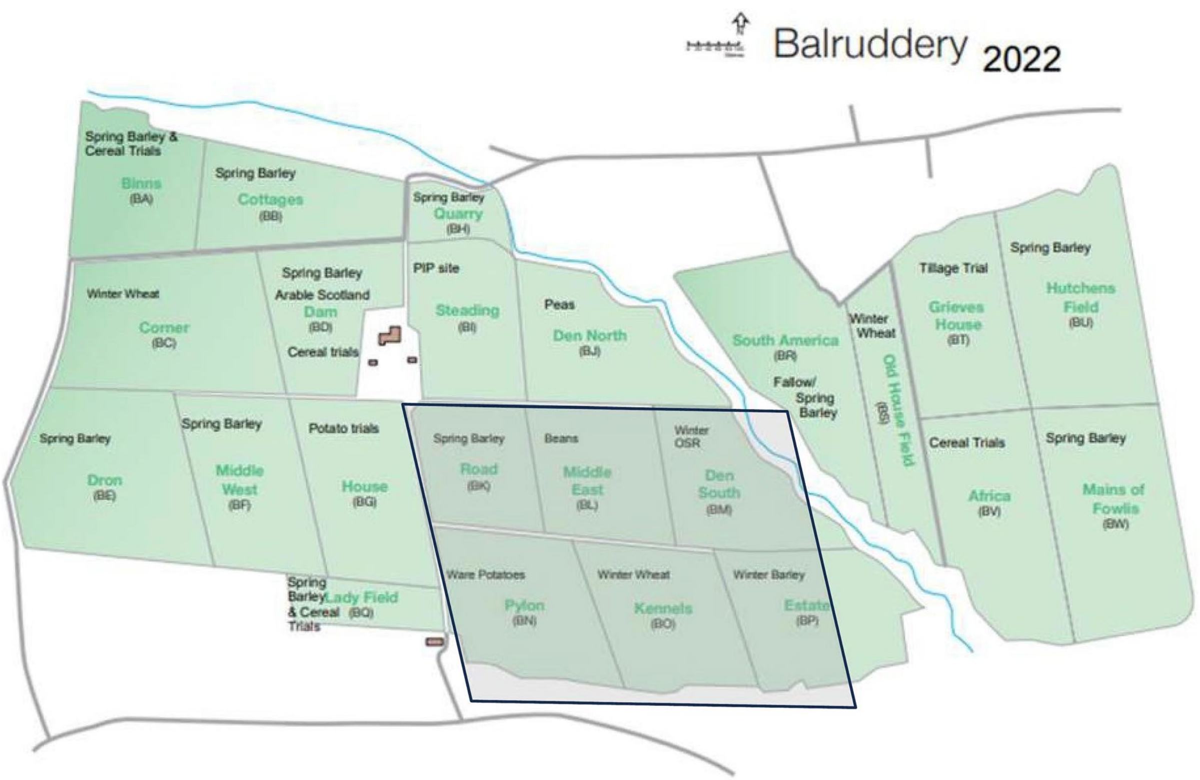

Fig. 3 CSC (bounded) and adjacent commercial field-production locations of 'spring barley' following spring barley on Balruddery Farm (2022)

standard conventional practices for arable cropped systems across Scotland.

N-fertiliser application rates were guided by recommended practices, such as the SRDP Technical Note TN731 (Sinclair et al. 2022). This guide provides detailed recommendations for N-fertiliser application based on various factors including crop type, previous crop, soil type, and expected yield variations due to N adjustments. For instance, after field beans, which leave substantial residual N in the soil, it is recommended that the N fertiliser application for spring barley is reduced by 20 kg ha^{-1} (a reduction from 130 to 110 kg ha^{-1}) (Sinclair et al. 2022). Maluk et al. (2022), working at the same CSC site using ^{15}N natural abundance methods, confirmed that field bean obtained most of its nitrogen through BNF, with %Ndfa values consistently high across all seasons (c. 80% in 2012–2013, > 90% in 2014–2015). This confirms that the rhizobium–legume symbiosis was functional throughout the experimental period, providing the mechanistic basis for the observed N-fertiliser savings.

Life cycle inventory (LCI) modelling

All foreground data (fertiliser types and quantities, pesticide active ingredients and application rates, diesel consumption for field operations, and crop yields) were recorded annually at the CSC and on commercial comparator fields. Background life cycle inventory data were sourced from the Ecoinvent v3.9 database (Wernet et al. 2016) using the Cut-off system model. Key background processes included ammonium nitrate production for fertiliser inputs, region-specific pesticide active ingredient production, and diesel combustion in agricultural machinery. Field-level N_2O emissions (direct and indirect) were modelled using the emission factors embedded in the Ecoinvent processes, which follow IPCC methodology. Ammonia (NH_3) volatilisation and nitrate (NO_3^-) leaching were similarly included via Ecoinvent's built-in emission profiles. Crop residue-N contributions from field beans were quantified using the BNF and residue-N data reported by Maluk et al. (2022) at the CSC, who measured residual N of 50–110 kg N ha^{-1} depending on season. Life cycle inventory modelling was conducted in openLCA 2.1.0.

Life cycle impact assessment

Life Cycle Impact Assessment (LCIA) was conducted using the EF 3.1 impact assessment method. This impact assessment method has been developed by the European Commission to be used in the context of the Environmental Footprint (EF) initiative (European Commission 2019). Results are presented for 6 priority impact categories pertaining to agricultural systems, namely Acidification, Climate Change (GWP100), Eutrophication(freshwater), Ozone Depletion, Resource use (fossils), Water Use. Acidification and Eutrophication (freshwater) are crucial as they reflect the environmental consequences of fertilizer use, which can lead to increased soil acidity and nutrient runoff into water bodies, respectively (Frischknecht et al. 2016). Similarly, Climate Change (GWP100) is essential for evaluating greenhouse gas emissions from agricultural practices, while Ozone Depletion, Resource Use (fossils), and Water Use are integral for assessing the broader environmental impacts, including depletion of the ozone layer, fossil resource utilization, and water management in barley production (ISO 14040:2006; ISO 14044:2006). Analyses were undertaken using openLCA 2.1.0, MS Excel, and Python.

Combined index for correlation analysis of several factors on spring barley yield

To understand the basis for observed barley yield fluctuations, further analysis was undertaken. Initially, the Pearson correlation coefficients were calculated. However, a more nuanced view emerged when an innovative index combining humidity, maximum temperature and the yields of the previous field bean crops was created using Python and Scikit-learn (Pedregosa et al. 2011). To develop the composite index, it was needed to standardise the scales of the selected variables (humidity, previous year's field bean yield, and maximum temperature), using Scikit-learn's "MinMaxScaler". This scaling technique adjusts the data to a common scale without distorting differences in the ranges of values, employing the formula:

$$X_{scaled} = \frac{(X - X_{min})}{(X_{max} - X_{min})}$$

This transformation ensures that each variable contributes equally to the analysis by converting their measurements to a 0 to 1 scale. Given the strong negative correlation of maximum temperature with yield, an inverse transformation was applied:

$$X_{temp} = 1 - X_{scaled}$$

Output was squared to amplify its significant adverse impact. The final step involved assigning weights to each scaled and transformed variable according to the absolute values of their correlation coefficients with yield. This weighting process allows for a weighted mean calculation of the variables, ensuring that those with a stronger influence on yield are more heavily represented in the index. By aggregating these variables into a single metric using the formula:

$$\text{Index} = \Sigma(w_i * X^i)$$

where w_i are the weights and X_i are the transformed, scaled values, the index offers a refined view of the interplay between environmental conditions and the effects of previous crops on yield outcomes.

Statistical analysis

Differences in yield, N-fertiliser use, pesticide use, and LCA impact scores between the FB–SB and SB–SB sequences were assessed using two-sided paired t-tests (scipy.stats.ttest_rel; Python v3.10/SciPy), treating the five crop-sequence years as paired observations. Normality of paired differences was checked using the Shapiro–Wilk test prior to testing; the yield differences did not significantly depart from normality ($W = 0.809$, $p = 0.096$). Effect sizes are reported as Hedges' g. An α of 0.05 was used; given $n = 5$, results are interpreted alongside effect sizes and year-to-year consistency. Soil chemistry field-year means are reported descriptively; the small number of independent field-years precludes formal inference.

Results

Attributional LCA

The LCIA included a comprehensive assessment of environmental impacts across six main categories, reflecting the varied potential environmental consequences associated with the crop sequence systems at Balruddery Farm. These categories are integral for

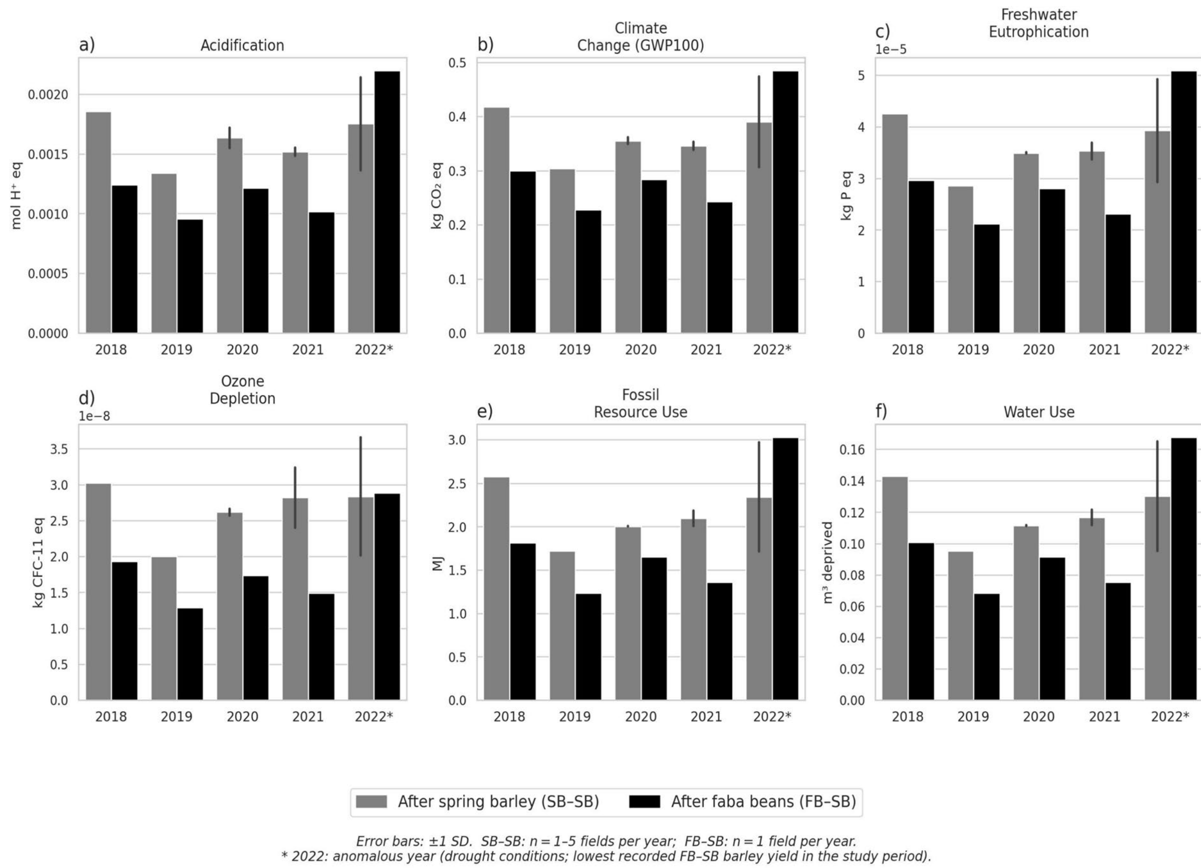

Fig. 4 Environmental burdens associated with 1 kg of barley grain across the acidification, climate change, freshwater eutrophication, ozone depletion, fossil resource use and water scarcity impact categories, for 'spring barley-spring barley' and 'spring field beans-spring barley' crop sequences. Error bars represent the standard deviation of annual means across the available fields for each crop sequence ($n = 1$ for FB–SB; $n = 2$–5 for SB–SB per year)

evaluating the sustainability of agricultural practices (Fig. 4).

Process contributions to the total environmental impact

Spring field beans preceding spring barley reduced the environmental impact of the subsequent spring barley crop across all six impact categories in four of five study years. Mean cradle-to-gate GWP100 for FB–SB was 0.33 ± 0.04 kg CO_2 eq kg^{-1} grain, 0.10 kg lower than SB–SB (paired t-test $p = 0.195$; g = 0.60; 95% CI = [−1.52, 0.32]). Acidification showed the only significant paired difference ($\Delta = 0.0006$ mol H^+ eq; $p = 0.035$; g ≈ 1).

Analysis of the process contributions (Fig. 5) to the overall environmental impact of spring barley production in 2021 highlights that synthetic N-fertiliser use appears as the dominant factor across the impact categories, contributing to over 60%.

The climate change impact shows higher values for continuous barley cultivation compared to the crop sequence with field beans (Magarey 1999). In 2018, the impact for barley following barley was 0.417 kg CO_2 eq, which was 39.5% higher than the 0.299 kg CO_2 eq recorded when barley followed field beans. By 2022, this impact had increased to 0.485 kg CO_2 eq for continuous barley, showing a 16.3% rise from 2018, while the impact for barley after field beans had grown to 0.336 kg CO_2 eq, a smaller increase of 12.4% over the same period.

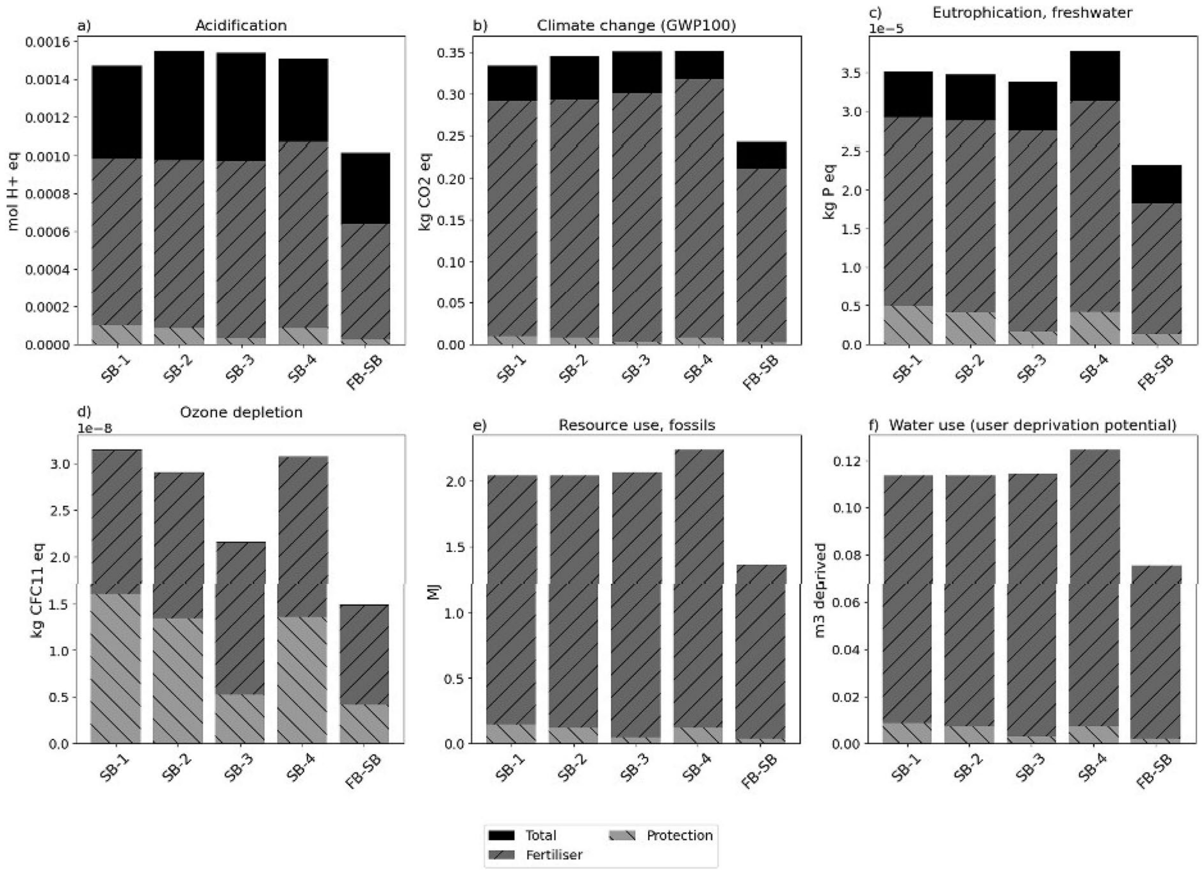

Fig. 5 Contributions of the main two processes determining environmental impact of cropping, specifically: Pesticide application ("Protection"), and N-fertiliser application ("Fertilisation"). The contribution percentages are expressed relative to spring barley (SB) yield in 2021 across 5 different fields: 4 commercial, 1 experimental (at the CSC; conventional field half). Contributions are consistent across all years, apart from 2022. Where crop sequences are: [SB–SB] in commercial fields, or [FB– SB]

Resource use in terms of fossil fuels also shows a trend favouring the field bean inclusive crop sequence. In 2018, resource use for continuous barley was 2.6 MJ, which was 44.4% higher than the 1.8 MJ recorded when barley followed field beans. By 2022, the resource use for continuous barley had increased to 3.0 MJ, a rise of 15.4% from 2018. Meanwhile, resource use for barley after field beans was 2.1 MJ, marking a 16.7% increase over the same period.

Lastly, water use (user deprivation potential) shows an increasing trend over the years, particularly for continuous barley cropping. In 2018, water use was 0.143 m^3 for barley following barley, showing a 41.6% higher consumption than the 0.101 m^3 recorded when barley followed field beans. By 2022, water use for continuous barley had risen to 0.168 m^3, marking an increase of 17.5% from 2018, while for barley after field beans, it had grown to 0.118 m^3, an increase of 16.8%.

The anomaly observed in 2022, where FB–SB yields fell below those of SB–SB, is discussed in Sect. 4.2.

N-fertiliser use, crop residue-N, pesticide use, and crop yield data.

Mean mineral-N input was **93 ± 9 kg ha^{-1} (FB) vs 104 ± 7 kg ha^{-1} (SB); Δ = −10.6 kg; *p* = 0.076; g = 1.08**. Average barley yield advantage after beans was + **1.2 t ha^{-1}** but non-significant in the five-year paired test ($p = 0.401$). A large effect size was observed for pesticide use (**g = 2.37; *p* = 0.007**).

Pesticide applications to spring barley following field beans were lower (ca. 2x) compared to the spring barley-spring barley crop sequence.

The grain yields of spring barley crops after field beans were higher in all years (apart from 2022) compared to those following spring barley (Table 3; Fig. 6), by an average of 1.2 t ha^{-1}. In 2022, a yield-trend reversal was observed where SB–SB yields exceeded those of FB–SB (Fig. 4 & Fig. 6).

In 2022, as the yields for spring barley following field beans declined, the inputs used in cultivation—maintained at similar or slightly reduced levels—were spread over fewer kilograms of harvested product. This results in a higher per kilogram environmental impact in all categories, increasing average impact of spring barley after field beans by almost two times (Fig. 4). Essentially, lower yields mean that each kilogram of barley grain carries a larger share of the total environmental burden incurred during the growing season.

Weather influence

Data gathered from the Met. office for Eastern Scotland

The weather data show significant climatic variation over the study period, with 2022 characterised by

Table 3 Life cycle inventory summary for spring barley production in FB–SB (CSC, conventional) and SB–SB (commercial comparator) sequences. All values are per hectare of spring barley crop

Year	Sequence	N-fertiliser (kg N ha^{-1})	Pesticide applications (n)	SB Yield (t ha^{-1})	Preceding FB yield (t ha^{-1})
2018	FB–SB	110	1.84	6.45	9.47
2019	FB–SB	86	1.32	7.4	4.00
2020	FB–SB	90	1.42	5.79	6.61
2021	FB–SB	90	1.7	7.08	4.73
2022	FB–SB	90	0.84	3.13	2.72
Mean ± SD	**FB–SB**	93 ± 10	1.42 ± 0.4	5.97 ± 1.68	**5.51 ± 2.63**
2018	SB–SB	110	5.25	4.60	—
2019	SB–SB	105	2.55	6.58	—
2020	SB–SB	90	3.11	4.90	—
2021	SB–SB	110	3.13	5.76	—
2022	SB–SB	104	3.32	4.99	—
Mean ± SD	**SB–SB**	104 ± 8	3.47 ± 1.0	5.37 ± 0.80	**—**

SB–SB values are means across 1–5 commercial fields per year (see Table 2). Pesticide applications include herbicides, fungicides, and desiccants

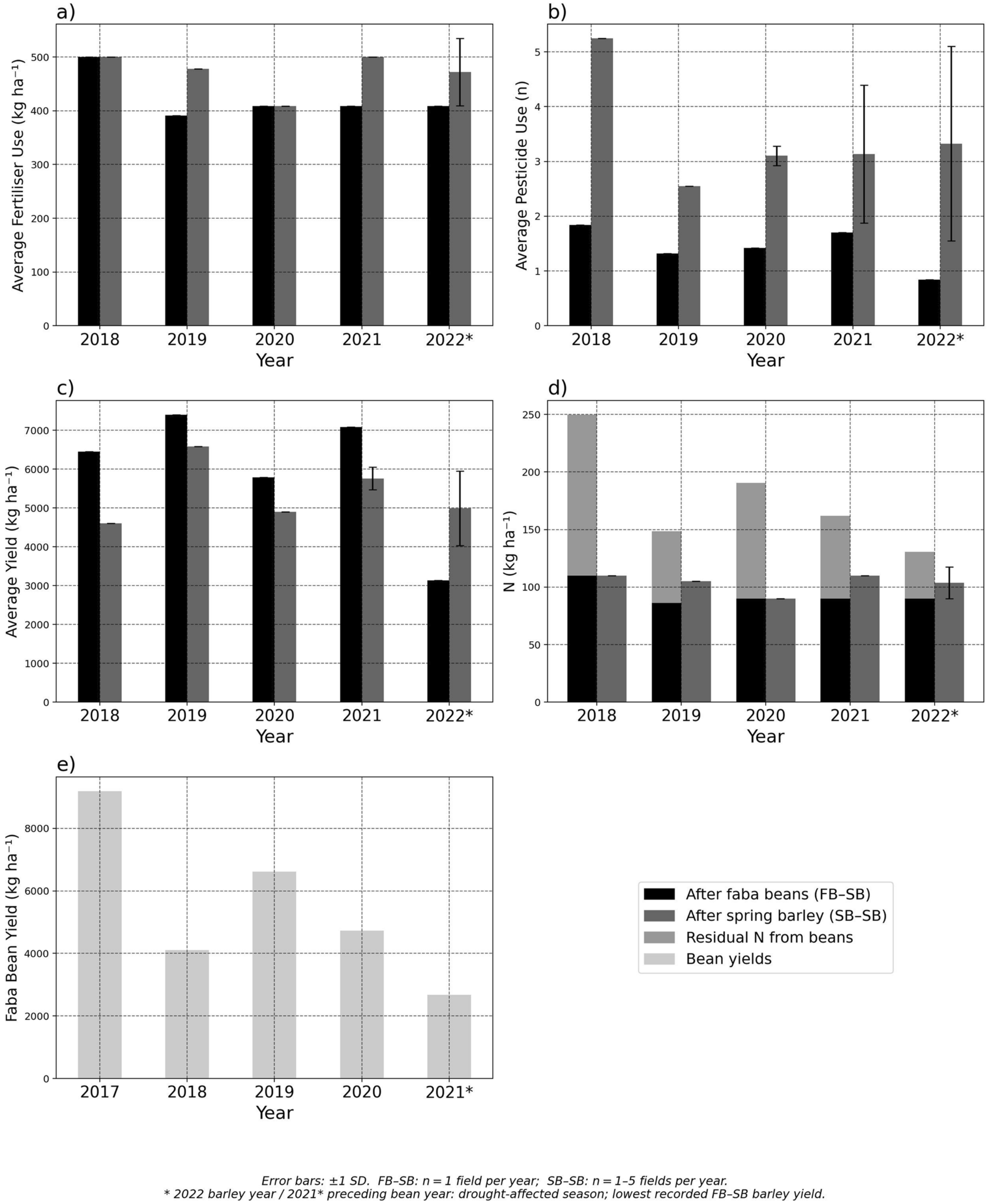

Fig. 6 Fertiliser and pesticide usage to produce spring barley, accompanied by their respective yields; also, field bean yields for preceding years. Residual N from the previous year's legumes have been calculated following data provisions of Maluk et al. 2022. Error bars: ± 1 SD. FB–SB: $n = 1$ field per year; SB–SB: $n = 1$–5 fields per year. * 2022: Anomalous year (drought; lowest recorded FB–SB barley yield)

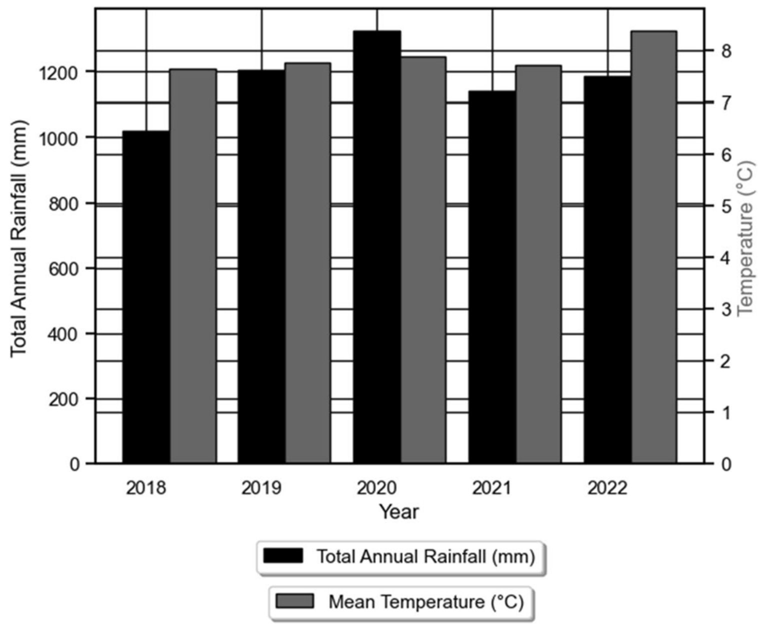

Fig. 7 Total annual precipitation and mean air temperatures, from 2018 to 2022

markedly higher temperatures and lower precipitation compared to other years (Fig. 7).

Soil-N dynamics due to field beans

The yield and N dynamics associated with field beans are reported below. The CSC field beans have demonstrated varying yields from 2017 to 2021 (Fig. 6), being greatest in 2017, reducing in 2018, and increasing again in 2019 and 2020, before its lowest in 2021. These fluctuations in yield may impact available soil-N for the following crop and examining the impact of field beans on N-fertiliser use in subsequent barley crops reveals no direct correlation between the estimated residual N left by field beans and the actual fertiliser application rates applied in the following years. Despite varying amounts of N being available after field bean harvests, the data shows that farmers did not adjust the quantity of fertiliser applied to the subsequent barley crops accordingly.

To provide additional context on the soil conditions associated with the FB–SB rotation, soil organic carbon (SOC), total soil nitrogen (N%), C:N ratio, and pH (H_2O) were extracted from the CSC long-term soil monitoring dataset. Mean values across the five field-years were: NO_3–N 5.0 ± 3.1 mg kg^{-1}, NH_4–N 2.2 ± 0.4 mg kg^{-1}, and pH 6.07 ± 0.14 (n = 5 field-years); SOC 2.84 ± 0.16%, total N 0.24 ± 0.04%, and C:N 12.4 ± 2.4 (n = 3 field-years with available elemental data: 2018–2020). The CSC-wide Conventional mean across the study period (2018–2022, all fields) was: NO_3–N 4.1 ± 2.8 mg kg^{-1}, SOC 2.65 ± 0.93%, C:N 11.6 ± 2.2, and pH 6.05 ± 0.25. These values indicate that the FB–SB spring barley fields sit within the normal range of CSC soil conditions. The small number of independent field-years (n = 3–5) and the absence of paired soil measurements from commercial SB–SB fields preclude formal statistical inference or direct cross-system comparison.

Discussion

Yield and impact benefits

This study tested two predictions: (H1) that incorporating spring field beans before spring barley would increase spring barley grain yields, and (H2) that the FB–SB sequence would reduce the environmental impact per unit of barley grain produced. H1 was supported in four of the five crop-sequence years, with a mean yield advantage of +1.2 t ha^{-1} following field beans although the paired t-test did not reach statistical significance (p = 0.401) given the small sample size (n = 5). In 2022, the yield advantage was reversed under drought conditions (see Section 4.2), suggesting that the predicted yield benefit of H1 may be conditional on adequate moisture availability and sufficient preceding legume performance (Bowles et al. 2020). H2 was supported across all six impact categories in four of five years: mean GWP_{100} was reduced by 0.10 kg CO_2 eq kg^{-1} grain in FB–SB relative to SB–SB (g = 0.60; p = 0.195), and acidification showed a statistically significant reduction (p = 0.035; g ≈ 1). The exception was again 2022, when lower FB–SB yields inflated per-kg impacts. These results concur with the broader meta-analytic evidence that legume pre-crops enhance cereal yields and reduce environmental burdens (Zhao et al. 2022; Martínez-Velasco et al. 2018) but suggest that the benefits are conditional on adequate legume performance and favourable weather in the cereal year.

Weather-driven variability: The 2022 drought case

The 2022 outcome, in which FB–SB yields fell below SB–SB, should not be interpreted as a failure of the legume pre-crop effect per se, but rather as evidence that the predicted yield benefit (H1) is conditional on the interaction between legume performance and subsequent growing-season weather. In 2021, field bean yields were at their lowest (Fig. 6), implying reduced residue-N provision; the 2022 growing season was then characterised by markedly higher temperatures and lower precipitation (Fig. 7). Under these conditions, the N-credit from the legume phase may have been insufficient to offset the yield penalty imposed by drought. This context-dependent framing aligns with the combined index analysis (Table 4), which identifies humidity and prior bean yield as the dominant predictors of barley yield, and highlights the conditions under which the rotation benefit is expressed or attenuated.

Such measures, with potential to help ensure the productivity and crop-rotation-potential efficiency of field beans, include: best agronomic practices concerning soil management and pre pulse crop preparation; implementation of integrated soil and water management practices; use of resilient climate-change-shock tolerant agronomic approaches e.g., intercropping (Brooker et al. 2024); the incorporation of catch-crops (to capture residual-N post field bean harvest); and/or resilient cultivars (to water-deficit, heat-, and/or flooding stresses) (Stagnari et al. 2017; Appiah et al. 2023). Cover cropping can improve soil moisture retention, also mulching these can reduce soil evaporation. Additionally, drip irrigation systems can optimise water use efficiency, and soil organic matter enhancement through the application of compost or organic amendments may also be beneficial; as can cultivation in ‘mixed systems’ (i.e., including farm animals), where animal manure is applied ahead of field bean cultivation. In addition to field beans, other pulse crops such as peas may also be considered as more suitable for inclusion in spring barley production systems; since studies have shown that pea varieties can maintain higher yields compared to field beans under drought conditions (Tanaka et al. 2010).

Nitrogen dynamics and fertiliser optimisation

It is also possible that spring barley N-fertiliser applications need to be more accurately aligned with the previous legume crops yield (and soil N status at barley sowing). For example, current guidelines for the UK (RB209; AHDB, 2017), are based on general outcomes of legume performance. However, these guidelines do not account for the variability in legume productivity and subsequent residue (N) contribution to the soil which can fluctuate significantly due to environmental factors, pest pressures, soil qualities, and other unforeseen circumstances. A ‘static approach’ to synthetic N-fertiliser application, where adjustments are not made in response to the natural N contributions from field beans, have implications for the yield and yield qualities (target markets and commercial value) of the following crop (spring barley). By not reducing N-fertiliser use in response to higher residual N levels, there is a missed opportunity to optimise resource use and potentially enhance the

Table 4 Correlation coefficients between environmental/agronomic variables, previous field bean yield, and spring barley yield, including combined index values

Attribute	Yield
Fertiliser	0.06
Pesticide	0.76
Max Temperature	−0.96
Min Temperature	−0.82
Mean Temperature	−0.94
Precipitation	0.50
Wind Speed	−0.69
Humidity	0.96
Previous Bean Yield	0.39
Combined Index	0.97

environmental sustainability of the cropping system. Conversely, not increasing fertiliser use in years when residual N is low could risk under-nourishing the following crop, leading to reduced yields, increased environmental impacts of production; and can threaten feed-security.

In this study, the performance of field beans in 2021 was diminished in terms of yield and in-field residue provision, possibly below a minimum threshold (due probably to reduced levels of precipitation in 2021). This scenario, where it occurs in future, presents a challenge since fertiliser-N use of the crop following could be adjusted in-line with field bean grain yield. Our study suggests that adhering strictly to the guideline of reducing fertiliser-N by 20 kg (in the UK) in 2022 may have led to the diminished yield and higher environmental impacts of spring barley that year. So, while field beans can significantly benefit the following non-legume crop, benefits may not be fully realised if agronomic practices, such as synthetic N-fertiliser use is not appropriately aligned with earlier provisions. This may be due to a lack of information, conservative agricultural practices, or socioeconomic constraints that prevent farmers from adjusting their N-fertiliser strategies dynamically based on legume pre-crop performance, and soil available- N levels.

The weak correlation between mineral N-fertiliser input and barley yield in our dataset warrants further discussion. Despite the FB–SB sequence receiving consistently lower N inputs (mean 93 ± 9 vs 104 ± 7 kg N ha^{-1}), yields were generally higher, suggesting that residual N from BNF and other break-crop effects (e.g. disease suppression, improved soil structure) contribute to yield independently of applied fertiliser rates. This decoupling of applied N from yield response underscores the need for adaptive N management that accounts for prior legume performance and soil N status, rather than relying on fixed reduction guidelines (AHDB, 2017; Sinclair et al. 2022).

To understand the complex interaction of specific crop species, crop-sequence and weather effects more clearly the combined index (Table 3) provided a more holistic means by which factors determining spring barley yield may be elucidated. We found that humidity was significant, since this directly affects plant physiological processes such as photosynthesis and transpiration. High yields in field beans typically indicate high vegetative-biomass, BNF, and yield; with subsequent soil enrichment to benefit the following crop. Conversely, lower field bean yields may suggest diminished plant biomass, and compromised BNF which would negatively impact the subsequent crops.

The combined index's high correlation (predictive value) with yields—at least for the CSC—suggests that effective agricultural management should consider both environmental conditions affecting the field beans, and availability of the field beans legacy (residue) for the following crop. The synergistic effect of humidity and previous field bean crop performance highlights the interconnectedness of previous and current crop sequence conditions, where the benefits of the leguminous may be maximised under favourable weather conditions the following season; and/or in response to precision agriculture approaches involving crop and environmental monitoring, and adoption of remedial measures as necessary.

The findings reported here reinforce the importance of considering multiple variables in agricultural planning and supports the use of an integrated and dynamic approach to crop management. By acknowledging the compounding effects of weather and crop rotational history, farmers (or agronomists) can better predict yield outcomes and make more informed decisions to ensure the productivity and sustainability in farming systems.

This study has also shown that the performance and environmental benefits of a pulse-to-cereal crop sequence may be dependent on the success of the pulse crop. It was highlighted that the benefits of field beans, such as enhanced soil N levels and reduced need for synthetic N fertilisers for the following non-legume crop, are significant when the legume crop performs well, and the weather in the following year is also optimal. Also, field bean-based sequences showcased a reduction in pesticide usage, and highlights the potential of field beans as part of a IPM strategy; despite the biotic stresses influenced by annual variations in pest pressures and weather conditions. However, in years where field bean yields were low, and the weather conditions the following year were not humid (had a low annual rainfall); the subsequent barley crop did not appear to benefit from the field bean pre-crop. This has highlighted the necessity to re-evaluate strategies for climate-resilient barley cropping; including synthetic N-fertiliser application rates to avoid yield penalties, and environmental impact increases.

The environmental benefits observed in this study are underpinned by soil nitrogen dynamics driven by legume BNF. Maluk et al. (2022), working at the same CSC site, demonstrated that field bean derived c. 80–90% of its nitrogen from atmospheric fixation (%Ndfa), with total N fixation exceeding 300 kg N ha^{-1} in the highest-yielding season and residual N of 50–110 kg N ha^{-1}. This confirms that the rhizobium–legume symbiosis was fully functional at the CSC, providing the mechanistic basis for the reduced N-fertiliser inputs and associated reductions in N_2O emissions, acidification, and eutrophication observed in the aLCA. While the present study did not directly measure soil N mineralisation rates, microbial community composition, or arbuscular mycorrhizal fungal (AMF) associations—which may further contribute to the break-crop effect (Köpke and Nemecek 2010)—the Maluk et al. data confirm the primary BNF mechanism (Li et al. 2009). The soil chemistry data available from the CSC long-term monitoring dataset provide further context. FB–SB fields showed a numerically wider C:N ratio (15.0 vs 11.0) and higher SOC (2.73 vs 2.27%) compared to the CSC spring barley long-term baseline, consistent with bean residues and root turnover incorporating carbon-rich organic material into the soil organic matter pool (Virk et al. 2022). A wider C:N ratio may indicate that legume-derived organic nitrogen is held in slow-cycling fractions less susceptible to leaching than mineral NO_3^-, potentially providing sustained N release to subsequent crops and partially explaining the observed decoupling between applied fertiliser-N and barley yield. However, the small number of independent field-years and the confounding of field identity with rotation sequence mean these differences should be interpreted as indicative rather than confirmed. Direct soil N mineralisation rates, microbial community composition, and arbuscular mycorrhizal fungal (AMF) associations were not measured in this study; characterising these processes would strengthen future assessments of the below-ground mechanisms mediating the rotation benefit.

Precision agronomy for climate-resilient rotations

Consequently, it may be argued that to improve the sustainability and productivity of agricultural systems, N-fertiliser use guidance should accommodate adoption of a ‘precision agriculture’ approach. This can be achieved by developing adaptive management plans that allow for modifications in N-fertiliser application based on previous crop performance, and current environmental conditions: including contingency strategies for limited legume performance (low residue returns and/or grain yields).

Further investigation is also required to better understand the full range of factors influencing legume performance and their BNF capabilities (Jithesh et al. 2024). To avoid the risk of N deficiency, it may be necessary to identify a ‘field bean residue or yield thresholds’, below which spring barley fertiliser-N should not be reduced; or above which fertiliser-N may be avoided. Based on our findings and the correlation between field bean yield and residual N, a conservative threshold (for the CSC) might be set at around 3 t ha^{-1} of field bean yield for the CSC based system studied here. Below this yield, the standard practice of reducing N by 20 kg ha^{-1} may jeopardise the subsequent spring barley yield (in dry years). That is, this lower threshold would differ depending on differing pedo-climatic nature of different localities, and specific weather-years.

Implementing real-time soil (N) and weather monitoring technologies may also help farmers adjust N application rates based on actual system states, as opposed to predefined estimates. In this context, long-term studies such as the CSC, with continuous data collection can help serve as sentinel to helping realise precision agriculture approaches which are tailored for legume (field bean based) systems locally. Also, the approach may help inform more nuanced guidelines (e.g., RB209 (>AHDB, 2017)), for local and prevailing weather and soil conditions.

By continued research and optimisation of integrated cropping systems, the agricultural sector can strive to achieve greater food security, environmental sustainability, and resilience in the face of global challenges (Godfray et al. 2010).

Scaling legume–cereal sequences for national GHG cuts

Considering these insights in parallel with the 2023 spring barley production data: Scotland produced approximately 1.6 million tonnes of spring barley (Scottish Government, 2023), we can evaluate the theoretical GHG benefit of adopting spring field beans as a preceding crop for spring barley on a national scale. By adopting the average per hectare yield of 6.3 tonnes for spring barley after spring barley and, following our study, modelling an increase in spring barley after field bean yield by 1.2 tonnes per hectare (7.5 tonnes in total), a tentative extrapolation can be made. The total GHG emissions for spring barley production after field beans were calculated to be 456kt CO_2-eq. In contrast, the emissions for spring barley following another barley crop were 562 kt CO_2-eq. This represents a significant (ca. 20 %) reduction in GHG emissions when field beans are included in the crop sequence.

Thus, scaling up the use of field beans as a precursor across all spring barley production in Scotland could potentially reduce national GHG emissions by 106 kt CO_2-eq annually. In 2022, the emissions from arable land in Scotland were approximately 1.6 million tonnes of CO_2 equivalent (Mt CO_2-eq) (>Scottish Government, 2024). A reduction of 106 kilotonnes of.

CO_2 equivalent (kt CO_2-eq) by scaling up the use of field beans as a precursor in spring barley production would represent about 6.6% of the total emissions from arable land. This highlights the significant potential for reducing the carbon footprint of arable farming through sustainable crop management practices that include the inclusion of field beans (Branca et al. 2021).

Study limitations

Several limitations should be acknowledged. First, the use of adjacent commercial fields as the SB–SB comparator, rather than an internal randomised control, means that observed differences may partly reflect site-specific management and soil differences rather than purely preceding-crop effects; readers should interpret the comparison as representative of real farming contrasts rather than a controlled experiment. Second, the small sample size ($n = 5$ years) limits statistical power; however, the consistently large effect sizes suggest meaningful agronomic and environmental effects that warrant further investigation with larger datasets. Third, the combined index was derived from and evaluated on the same dataset, limiting its predictive validity; independent validation with data from additional sites and years is needed before the index can be used for management guidance. Fourth, soil health indicators such as N mineralisation rates, microbial community composition, and AMF colonisation were not directly measured in this study, and no 15N natural-abundance analysis was conducted to determine the proportion of nitrogen derived from the atmosphere (Ndfa%) in the field bean crops studied here. The BNF estimates reported (80–90% Ndfa, residual N of 50–110 kg N ha^{-1}) are drawn from Maluk et al. (2022), who conducted 15N analysis at the same CSC platform but in earlier seasons; direct confirmation for the study years 2018–2022 would strengthen the mechanistic argument. The CSC soil chemistry data presented in Sect. 3.3 provide descriptive evidence of elevated C:N ratios in FB–SB fields consistent with legume residue incorporation, but the small number of independent field-years precludes formal inference. Finally, the LCA relied on Ecoinvent background data that may not perfectly represent Scottish-specific production conditions for all input processes.

Conclusion

This study evaluates the influence of environmental and agricultural factors on the yields of spring barley following spring field bean cultivation. By conducting an aLCA the potential of a spring field bean pre-crop to maintain and/or increase the yields of the following spring barley crop under conditions of reduced inputs (synthetic N fertilisers, pesticide, and fossil fuel use) while lowering environmental impacts was proven in 4 of the 5 crop-sequence years studied. The findings also highlighted that such potential benefits cannot be assured in all years; and depend upon favourable weather conditions, and availability of bean-residue mineralisation (for the subsequent crop) too. Nevertheless, combining data on pre-crop field bean yields and cultivation-year environmental conditions for spring barley allowed a predictive index to be developed to guide decision makers on yield-safeguarding practices. The findings underscore the significance of integrated crop management and environmental stewardship as informed by environmental and crop monitoring to inform precision agronomy that optimises crop production and environmental sustainability.

The environmental benefits of integrating legumes like field beans into crop sequences are reaffirmed in this study: as the spring field bean inclusion before spring barley reduced environmental impacts across all 6 impact categories. However, to fully leverage these all crops in the rotation must be managed using informed best-practices that incorporate capacities to ensure best soil conditions and pre-empt the impacts of sub-optimal weather. Within this strategy, there is also a significant opportunity to improve the sustainability of crop production systems through more precise fertiliser applications. This approach not only reduces the environmental impact associated with excess fertiliser use but also helps in maintaining economic efficiency. Considering multiple environmental variables together, as demonstrated by the combined index, can provide a more accurate prediction of crop outcomes and facilitate more informed decision-making.

Acknowledgements JHI is supported by the Rural and Environment Science and Analytical Services (RESAS), a division of the Scottish Government. This work is also supported by the following projects: 'N efficient plants for Climate Smart arable cropping systems' (NCS) Project (Grant Agreement number 10043778, funded by DEFRA (Department for Environment, Food, and Rural Affairs (DEFRA; UK Government), and supported by InnovateUK; the European Commission funded 'Research and Innovation Action' projects: www.RADIANT-project.eu, www.econutri-project.eu, and, www.legumESproject.eu (Grant Agreement numbers

101000622, 101081858, and 101135512, respectively).

Data Availability The datasets generated and/or analysed during the current study are available from the corresponding author on request.

Declarations

The authors confirm that this study has not been published previously, that it is not under consideration for publication elsewhere, that its publication is approved by all authors and tacitly or explicitly by the responsible authorities where the work was carried out, and that, if accepted, it will not be published elsewhere in the same form, in English or in any other language, including electronically without the written consent of the copyright-holder.

Generative AI and AI-assisted technologies in the writing process During the preparation of this work the author(s) used ChatGPT to check grammatical errors and create alternatives for wordings. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

Competing Interests The authors declare that they have no competing interests.

References

AHDB (Agriculture and Horticulture Development Board) (2017) Nutrient management guide (RB209). Section 1: Principles of nutrient management and fertiliser use. AHDB, Stoneleigh, England. https://ahdb.org.uk/documents/RB209/RB209_Section1_WEB_2017-12-01.pdf

Altieri MA, Nicholls CI (2020) Agroecology and the reconstruction of a post-COVID-19 agriculture. J Peasant Stud 47(5):881–898. https://doi.org/10.1080/03066150.2020.1782891

Angus JF, Kirkegaard JA, Hunt JR, Ryan MH, Ohlander L, Peoples MB (2015) Break crop benefits in temperate wheat production. Field Crop Res 185:4–17. https://doi.org/10.1016/j.fcr.2015.10.008

Appiah M, Abdulai I, Schulman AH, Moshelion M, Dewi ES, Daszkowska-Golec A, Bracho-Mujica G, Rötter RP (2023) Drought response of water-conserving and non-conserving spring barley cultivars. Front Plant Sci 14:1247853. https://doi.org/10.3389/fpls.2023.1247853

Arvanitoyannis IS (2008) ISO 14040: life cycle assessment (LCA)–principles and guidelines. Waste Manag Food Ind 97–132

Balázs B, Kelemen E, Centofanti T, Vasconcelos MW, Iannetta PPM (2021) Integrated policy analysis to identify transformation paths to more sustainable legume-based food and feed value-chains in Europe. Agroecol Sustain Food Syst 45(6):931–953. https://doi.org/10.1080/21683565.2021.1884165

Barbieri P, Pellerin S, Nesme T (2017) Comparing crop rotations between organic and conventional farming. Sci Rep. https://doi.org/10.1038/s41598-017-14271-6

Beillouin D, Ben-Ari T, Malézieux E, Seufert V, Makowski D (2021) Positive but variable effects of crop diversification on biodiversity and ecosystem services. Glob Change Biol 27(19):4697–4710. https://doi.org/10.1111/gcb.15747

Bowles TM, Mooshammer M, Socolar Y, Calderón F, Cavigelli MA, Culman SW, Deen W, Drury CF, Garcia y Garcia A, Gaudin ACM, Harkcom WS, Lehman RM, Osborne SL, Robertson GP, Salerno J, Schmer MR, Strock J, Grandy AS (2020) Long-term evidence shows that crop-rotation diversification increases agricultural resilience to adverse growing conditions in North America. One Earth 2(3):284–293. https://doi.org/10.1016/j.oneear.2020.02.007

Branca G, Braimoh AK, Zhao Y, Ratii M, Likoetla P (2021) Are there opportunities for climate-smart agriculture? Assessing costs and benefits of sustainability investments and planning policies in Southern Africa. J Clean Prod 278:123847. https://doi.org/10.1016/j.jclepro.2020.123847

Brooker RW, Pakeman RJ, Adam E, Banfield-Zanin JA, Bertelsen I, Bickler C, Fog-Petersen J, George D, Newton AC, Rubiales D, Tavoletti S, Villegas-Fernández ÁM, Karley AJ (2024) Positive effects of intercrop yields in farms from across Europe depend on rainfall, crop composition, and management. Agron Sustain Dev 44(4):35. https://doi.org/10.1007/s13593-024-00968-2

European Commission (2019) European Platform on Life Cycle Assessment (EPLCA). https://eplca.jrc.ec.europa.eu/

Costa MP, Reckling M, Chadwick D, Rees RM, Saget S, Williams M, Styles D (2021) Legume-modified rotations deliver nutrition with lower environmental impact. Front Sustain Food Syst 5:656005. https://doi.org/10.3389/fsufs.2021.656005

Costa MP, Chadwick D, Saget S, Rees RM, Williams M, Styles D (2020) Representing crop rotations in life cycle assessment: a review of legume LCA studies. Int J Life Cycle Assess 25(10):1942–1956. https://doi.org/10.1007/s11367-020-01812-x

Curran MA (2015) Life cycle assessment student handbook. John Wiley & Sons

Davis AS, Hill JD, Chase CA, Johanns AM, Liebman M (2012) Increasing cropping system diversity balances productivity, profitability and environmental health. PLoS ONE. https://doi.org/10.1371/journal.pone.0047149

Duffy C, Styles D, Schestak I, Macgregor K, Jack F, Henn D, Black K, Iannetta PPM (2023) Optimising sustainability: circular pathways for Scotch Whisky distillery co-products. J Clean Prod 395:136436. https://doi.org/10.1016/j.jclepro.2023.136436

Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in Life Cycle Assessment. J Environ Manage 91(1):1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Freitag S, Verrall SR, Pont SDA, McRae D, Sungurtas JA, Palau R, Hawes C, Alexander CJ, Allwood JW, Foito A, Stewart D, Shepherd LVT (2018) Impact of conventional and integrated management systems on the water-soluble vitamin content in potatoes, field beans, and cereals. J Agric Food Chem 66(4):831–841. https://doi.org/10.1021/acs.jafc.7b03509

Frischknecht R, Fantke P, Tschümperlin L, Niero M, Antón A, Bare J, Boulay A-M, Cherubini F, Hauschild MZ, Henderson A, Levasseur A, McKone TE, Michelsen O, i Canals LM, Pfister S, Ridoutt B, Rosenbaum RK, Verones F, Vigon B, Jolliet O (2016) Global guidance on environmental life cycle impact assessment indicators: progress and case study. Int J Life Cycle Assess 21(3):429–442. https://doi.org/10.1007/s11367-015-1025-1

Gan Y, Hamel C, O'Donovan JT, Cutforth H, Zentner RP, Campbell CA, Niu Y, Poppy L (2015) Diversifying crop rotations with pulses enhances system productivity. Sci Rep 5:14625. https://doi.org/10.1038/srep14625

Godfray HCJ, Beddington JR, Crute IR, Haddad LJ, Lawrence D, Muir JF, Pretty J, Robinson S, Thomas SM, Toulmin C (2010) Food security: the challenge of feeding 9 billion people. Science 327:812–818. https://doi.org/10.1126/science.1185383

Goedkoop M, Oele M, Leijting J, Ponsioen T, Meijer E (2008) Introduction to LCA with SimaPro 7. PRé Consultants, Netherlands

Goedkoop M, Oele M, Leijting J, Ponsioen T, Meijer E (2016). Introduction to LCA with SimaPro (Report v5.2). PRé Sustainability

Graham PH, Vance CP (2003) Legumes: importance and constraints to greater use. Plant Physiol 131(3):872–877. https://doi.org/10.1104/pp.017004

Hawes C, Alexander CJ, Begg GS, Iannetta PPM, Karley AJ, Squire GR, Young M (2018) Plant responses to an integrated cropping system designed to maintain yield whilst enhancing soil properties and biodiversity. Agronomy (Basel) 8(10):229. https://doi.org/10.3390/agronomy8100229

Hawes C, Young MW, Banks G, Begg GS, Christie A, Iannetta PPM, Karley AJ, Squire GR (2019) Whole-systems analysis of environmental and economic sustainability in arable cropping systems: a case study. Agronomy (Basel) 9(8):438. https://doi.org/10.3390/agronomy9080438

Hayer F, Bonnin E, Carrouée B, Gaillard G, Nemecek T, Schneider A, Vivier C (2010) Designing sustainable crop rotations using Life cycle assessment of crop combinations. Proceedings of the 9th European IFSA Symposium, Vienna, Austria

Iannetta PPM, Hawes C, Begg GS, Maaß H, Ntatsi G, Savvas D, Vasconcelos M, Hamann K, Williams M, Styles D, Toma L, Shrestha S, Balázs B, Kelemen E, Debeljak M, Trajanov A, Vietoris V, Galanakis CM, Bebeli PJ, Wilkinson A (2021) A multifunctional legume value chain for Europe. Front Sustain Food Syst 5 692137. https://doi.org/10.3389/fsufs.2021.692137

ISO (2006) ISO 14044: Environmental management—Life cycle assessment—Requirements and guidelines. International Organization for Standardization, Geneva

Jensen ES, Peoples MB, Hauggaard-Nielsen H (2010) Faba bean in cropping systems. Field Crops Res 115(3):203–216. https://doi.org/10.1016/j.fcr.2009.10.008

Jithesh T, James EK, Iannetta PPM, Howard B, Dickin E, Monaghan JM (2024) Recent progress and potential future directions to enhance biological nitrogen fixation in faba bean (*Vicia faba* L.). Plant-Environ Interact 5:e10145. https://doi.org/10.1002/pei3.10145

Karkanis A, Ntatsi G, Lepse L, Hernández JAF, Vågen IM, Rewald B, Alsiņa I, Kronberga A, Balliu A, Olle M, Bodner G, Dubova L, Rosa E, Savvas D (2018) Faba Bean Cultivation – Revealing Novel Managing Practices for More Sustainable and Competitive European Cropping Systems. Front Plant Sci 9:1115. https://doi.org/10.3389/fpls.2018.01115

Khan A, Yar M, Khalid S, Elshikh MS, Akram HM, Ahmad I, Al-Tawaha AR, Ahmad M, Muhammad A, Ullah S, Ali I, Fahad S, Adnan M, Ali A (2021) Phenology, growth, productivity, and profitability of mungbean as affected by potassium and organic matter under water stress vs. no water stress conditions. J Plant Nutr 45(5):629–650. https://doi.org/10.1080/01904167.2021.1936025

Köpke U, Nemecek T (2010) Ecological services of faba bean. Field Crops Res 115(3):217–233. https://doi.org/10.1016/j.fcr.2009.10.012

Li C, Li X, Kong W, Wu Y, Wang J (2009) Effect of monoculture soybean on soil microbial community in the Northeast China. Plant Soil 330(1–2):423–433. https://doi.org/10.1007/s11104-009-0216-6

Magarey RC (1999) Reduced productivity in long term monoculture: where are we placed? Australas Plant Pathol 28(1):11–20. https://doi.org/10.1071/AP99002

Maluk M, Ferrando-Molina F, Lopez del Egido L, Langarica-Fuentes A, Yohannes GG, Young MW, Martin P, Gantlett R, Kenicer G, Hawes C, Begg GS, Quilliam RS, Squire GR, Young JPW, Iannetta PPM, James EK (2022) Fields with no recent legume cultivation have sufficient nitrogen-fixing rhizobia for crops of faba bean (*Vicia faba* L.). Plant Soil 472(1):345–368. https://doi.org/10.1007/s11104-021-05246-8

Martínez-Velasco A, Lobato-Calleros C, Hernández-Rodríguez BE, Román-Guerrero A, Álvarez-Ramírez J, Vernon-Carter E (2018) High intensity ultrasound treatment of faba bean (*Vicia faba* L.) protein: effect on surface properties, foaming ability and structural changes. Ultrason Sonochem 44:97–105. https://doi.org/10.1016/j.ultsonch.2018.02.007

Newton AC, Flavell AJ, George TS, Leat P, Mullholland B, Ramsay L, Revoredo-Giha C, Russell J, Steffenson BJ, Swanston JS, Thomas WTB, Waugh R, White PJ, Bingham IJ (2011) Crops that feed the world 4. Barley: a resilient crop? Strengths and weaknesses in the context of food security. Food Secur 3(2):141–178. https://doi.org/10.1007/s12571-011-0126-3

NFUS (2018) What we produce. https://www.nfus.org.uk/farming-facts/what-we-produce.aspx

Pedregosa F, Varoquaux G, Gramfort A, Michel V, Thirion B, Grisel O, Blondel M, Prettenhofer P, Weiss R, Dubourg V, Vanderplas J, Passos A, Cournapeau D, Brucher M, Perrot M, Duchesnay E (2011) Scikit-learn: Machine Learning in Python. J Mach Learn Res 12:2825–2830

Roberts M, Hawes C, Young M (2023) Environmental management on agricultural land: cost benefit analysis of an integrated cropping system for provision of environmental public goods. J Environ Manage 331:117306. https://doi.org/10.1016/j.jenvman.2023.117306

Rochester IJ, Peoples MB, Constable GA, Gault RR (1998) Faba beans and other legumes add nitrogen to irrigated cotton cropping systems. Aust J Exp Agric 38(3):253–260. https://doi.org/10.1071/EA97132

Shah KK, Modi B, Pandey HP, Subedi A, Aryal G, Pandey M, Shrestha J (2021) Diversified crop rotation: an approach for sustainable agriculture production. Adv Agric. https://doi.org/10.1155/2021/8924087

Sinclair A, Wale S, Bingham I (2022) Nitrogen recommendations for cereals, oilseed rape and potatoes. SRUC Technical Note TN731. https://www.sruc.ac.uk/media/eeelqian/tn731-nitrogen-recommendations-for-cereals-oilseed-rape-and-potatoes-update-31-10-2022.pdf

Stagnari F, Maggio A, Galieni A, Pisante M (2017) Multiple benefits of legumes for agriculture sustainability: an overview. Chem Biol Technol Agric. https://doi.org/10.1186/s40538-016-0085-1

Tanaka DL, Liebig MA, Krupinsky JM, Merrill SD (2010) Crop sequence influences on sustainable spring wheat production in the Northern Great Plains. Sustainability 2(12):3695–3709. https://doi.org/10.3390/su2123695

The Scottish Government (2019) Scottish crop map 2019. https://www.gov.scot/publications/scottish-crop-map-2019/

The Scottish Government (2023) Cereal and oilseed rape harvest: Final estimates 2023. https://www.gov.scot/publications/cereal-and-oilseed-rape-harvest-2023/

The Scottish Government (2024) Scottish agriculture greenhouse gas emissions and nitrogen use: 2022–23. https://data.gov.scot/scottish-agriculture-greenhouse-gas-emissions-nitrogen-use-2022-23/

Vasconcelos MW, Grusak MA, Pinto E, Gomes A, Ferreira H, Balázs B, Centofanti T, Ntatsi G, Savvas D, Karkanis A, Williams M, Vandenberg A, Toma L, Shrestha S, Akaichi F, Barrios CO, Gruber S, James EK, Maluk M, Iannetta P (2020) The Biology of Legumes and Their Agronomic, Economic, and Social Impact. In: Hasanuzzaman M, Araújo S, Gill SS (eds) The Plant Family Fabaceae: Biology and Physiological Responses to Environmental Stresses. Springer Singapore, pp 3–25. https://doi.org/10.1007/978-981-15-4752-2_1

Virk AL, Lin B-J, Kan Z-R, Qi J-Y, Dang YP, Lal R, Zhao X, Zhang H-L (2022) Chapter Two – Simultaneous effects of legume cultivation on carbon and nitrogen accumulation in soil. In: Sparks DL (ed) Advances in Agronomy, vol 171. Academic Press, pp 75–110. https://doi.org/10.1016/bs.agron.2021.08.002

Weisberger D, Nichols VA, Liebman M (2019) Does diversifying crop rotations suppress weeds? A meta-analysis. PLoS ONE. https://doi.org/10.1371/journal.pone.0219847

Wernet G, Bauer C, Steubing B, Reinhard J, Moreno-Ruiz E, Weidema B (2016) The ecoinvent database version 3 (part I): overview and methodology. Int J Life Cycle Assess 21:1218–1230. https://doi.org/10.1007/s11367-016-1087-8

Zhao J, Chen J, Beillouin D, Lambers H, Yang Y, Smith P, Zeng Z, Olesen JE, Zang H (2022) Global systematic review with meta-analysis reveals yield advantage of legume-based rotations and its drivers. Nat Commun. https://doi.org/10.1038/s41467-022-32464-0