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Effects of barley-pea intercropping on soil carbon, crop productivity, and grain quality in a low-input temperate agroecosystem

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Abstract

Intercropping has the potential to help adapt arable agriculture to climate change, but its effects on soil carbon and crop production in temperate agroecosystems remain uncertain. This study examined the effects of temperate intercropping systems on soil carbon and crop productivity. The study focused on two barley (*Hordeum vulgare* L.) cultivars with contrasting phenotypic traits (high-yielding vs. water stress-tolerant) intercropped with pea (*Pisum sativum* L.) and their three corresponding monocultures systems, grown without agrochemical inputs. During a 2-year field experiment in Scotland, soil properties were investigated on six occasions at two depths, upper (<5 cm) and lower (25–30 cm) topsoil. Crop yields and grain quality (i.e., grain carbon and nitrogen concentrations) were also assessed. Despite peas failing before harvest, intercropped barley exhibited yield gains of 90–132 g m^{-2} based on net effect metric and up to 10% in partial land equivalent ratio compared to barley monocultures. By the second year, total carbon concentration increased by 8.1% in the upper topsoil in intercrop of high-yielding barley cultivar compared to its monoculture (23.6 g kg^{-1}). Also, grain carbon and nitrogen concentrations were higher for intercropped barley than monocultures, with the stress-tolerant cultivar increasing grain carbon concentration by 5.7% over its monoculture. These findings demonstrate for the first time in temperate agroecosystems that low-input barley-pea intercropping could at least maintain or increase soil carbon and grain quality without compromising yields but dependent on barley cultivar traits. Intercropping can therefore potentially help adaptation to and mitigation of climate change in agroecosystems.

Abbreviations: LER, land equivalent ratio; NE, net effect; pLER, partial land equivalent ratio; VWC, volumetric water content.

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Plain Language Summary

Farmers need new methods to keep their land healthy and productive as the climate changes. Intercropping, which is planting crops together, may help solve this problem. However, we still do not know how this practice affects soil and crops in colder regions. This study looked at how growing barley with peas affects soil carbon and crop yield in Scotland without using chemicals. Two types of barley were tested, one that gives high yields and one that can survive drought. Even though the peas failed before harvest, the barley grown in intercropping still produced more yields (90–132 g m^{-2}) than when grown alone. Soil carbon and grain quality also improved, especially with the high-yielding barley. These findings suggest that intercropping could help improve soil and crop quality without reducing yields.

1 | INTRODUCTION

The agricultural and agro-allied industries are facing multiple challenges associated with meeting an ever-increasing global demand for food while also adapting to the pressures of climate change (FAO et al., 2023; Kumar et al., 2022). The changing climate is projected to have huge impacts on land and nutrient availability for growing crops for human consumption and other end-uses, such as biofuels and brewing and distilling products (Gomez-Zavaglia et al., 2020; Hatfield et al., 2020). Global disruptions to precipitation patterns and rising temperatures are already intensifying pressure on land resources, causing low agricultural yields and food shortages (Dai, 2021; IPCC, 2023). Even temperate regions, which are not usually associated with water shortages, are projected to be at drought risk. For instance, drought occurrence in Scotland is predicted to increase by approximately 50% by 2050, affecting many economically important sectors, especially the food and drink industry (Visser-Quinn et al., 2021). Within this context, soil carbon (C) is crucial for agricultural sustainability and climate change mitigation (Bossio et al., 2020; Nazir et al., 2024). With growing concerns about the greenhouse gas emissions from agriculture, which account for 18% of Scotland's national total (Eory et al., 2022), there is increasing interest in management practices that can contribute to enhancing C storage (Farooqi et al., 2020; Nazir et al., 2024). These practices offer potential carbon credit benefits for farmers while addressing the climate crisis (Raina et al., 2024). In addition to the need for C sequestration in soil, long-term sustainability of agroecosystems depends on maintaining and improving soil health, which is strongly related to soil C concentration (Farooqi et al., 2020; Milne et al., 2015).

Conventional European arable agriculture practices are based on monoculture systems with reliance on the intensive use of agrochemical inputs, such as synthetic fertilizers and pesticides (European Environment Agency, 2023). This typically leads to adverse effects on the environment, such as greenhouse gas emissions and pollution of groundwater (Messean et al., 2021). To adapt to the climate crisis and transition toward sustainable arable farming, nature-based solutions and other innovative practices provide potential for growing crops with reduced inputs while maintaining yield, increasing C sequestration, and improving soil health (e.g., Anderson et al., 2020; Messean et al., 2021; Verret et al., 2020). One such practice is intercropping (also referred to as co-cropping), which is the growing of two or more crop species or cultivars concurrently in the same field in mixed, strip, row, or relay patterns. Crops with complementary resource use traits that could be combined include cereal—cereal, cereal—legume, legume—legume, or non-legume—cereal (Stomph et al., 2020). Intercropping is most common in non-temperate regions, especially in China, and mostly involves maize, wheat, and soybeans (Hong et al., 2017; W. Wang et al., 2024). In these regions, the potential benefits are well-documented in global reviews and meta-analyses, including improved yields, efficient use of resources, soil nitrogen (N) fixation, increased biodiversity, higher soil C, resilience to environmental stresses, and enhanced land productivity (C. Li et al., 2020; Stomph et al., 2020).

Intercropping is still sparse but now increasingly encouraged in temperate regions where common practice involves monoculture systems, which use large amounts of fertilizer to overcome soil nutrient deficiency (Brooker et al., 2024a; Reckling et al., 2022; Rodriguez et al., 2021). In temperate regions, the most viable crop combinations are cereal-legume combinations due to their adaptability to the climate and soil, and because legumes can be used to reduce the need for mineral fertilizer inputs to the cereals (Rodriguez et al., 2020; Weih et al., 2021). Potential benefits of intercropping in temperate agroecosystems are higher yields (Brooker et al., 2024a; Mbanyele et al., 2024; Pappa et al., 2012; Weih et al., 2021), improved land productivity and biodiver-

sity (Brooker et al., 2015; Chapagain & Riseman, 2014a), and enhanced N fixation (Chapagain & Riseman, 2014b; Rodriguez et al., 2020). However, previous studies have mainly focused on the effects on aboveground processes and benefits (Landschoot et al., 2023) and have not fully explored the potential for soil C sequestration and important effects on soil properties (Homulle et al., 2021; Yu et al., 2022). The potential of intercropping to provide resilience to environmental stress in temperate agroecosystems, including drought and temperature rise, is also largely unknown.

Another relatively unexplored area in terms of the uncertainty in benefits of intercropping is the role of genotypic/cultivar traits (Homulle et al., 2021). Genotypic traits that are best suited in mixtures for enhancing yield, productivity, sustainability, and ecosystem services under low inputs and varying environmental conditions have not yet been fully identified (Haug et al., 2023; Yu et al., 2022). For instance, high-yielding cultivars in monocultures usually demonstrate higher yields under optimal conditions, but with varied impact on soil C (Devkota et al., 2021; Schreiber et al., 2024; Van de Broek et al., 2020). On the other hand, water stress-tolerant cultivars with larger numbers of root hairs have demonstrated stable yields under optimal conditions but performed better at improving soil structure and resource use, especially under environmental stress (Marin et al., 2021, 2022). However, it is uncertain how these cultivars will perform when intercropped.

To date, only Brooker et al. (2024b) have examined the impact of intercropping on total soil C in Scotland, a temperate region. Their study found reduced soil C concentration in the upper 10-cm soil depth under intercropping in multiple crop combinations and field sites but suggested possible C sequestration in deeper soil layers. Also, the methodology of the study was limited by combining diverse crop cultivars with different phenotypic traits, without consideration of potential cultivar trait-specific responses. More research is therefore needed on the impact of intercropping on soil C, environmental sustainability, and productivity in these temperate regions, with consideration on the role of cultivar traits.

Typical for a temperate agroecosystem, this research focused on the intercropping of spring barley (*Hordeum vulgare* L.), due to its importance to the Scottish/UK food and drink economies, with pea (*Pisum sativum* L.) as an N-fixing plant often used for animal feed. Low-input management with no agrochemical inputs was considered and included two different barley cultivars, selected for contrasting phenotypic traits (high-yielding and water stress-tolerant cultivars). This study specifically aimed to examine the short-term effects of barley-pea intercropping systems on soil C and crop productivity. The objectives were to:

1. investigate the spatiotemporal dynamics of soil C, N, and physical properties across different cropping systems;
2. assess differences in these soil properties between intercropping systems and their respective monocultures;
3. compare the productivity and grain nutrient concentration of barley in intercropping with those in monocultures;
4. evaluate the role of barley cultivar traits on the performance of intercropping systems.

Core Ideas

- Effects of barley-pea intercropping varied with barley cultivar trait.
- Crop and land productivity was enhanced by intercropping compared to monoculture.
- Soil carbon in the upper topsoil was higher in intercropping than monoculture but also cultivar dependent.

It was hypothesized that (1) barley-pea intercropping systems will at least maintain or increase soil C, crop productivity, and grain nutrient concentration compared to monocultures, and (2) barley cultivar traits will affect the impacts of barley-pea intercropping on soil carbon and crop performance.

2 | MATERIALS AND METHODS

2.1 | Study site, experimental design, and field management

The study site is located at Balruddery Farm of The James Hutton Institute (56.48°N, 3.11°W; 67–163 m above sea level), an arable research farm near Dundee, Scotland, UK (Figure 1). The research site is located within a temperate region (Cfb under the Köppen climate classification) with a long-term average annual precipitation of 800 mm and daily temperature of 8.6°C (Hawes et al., 2018). The soil at the farm is Cambisol according to the World Reference Base for Soil Resources and is predominantly clay loam to sandy loam in texture (Brown et al., 2021; Hawes et al., 2018). Stone content ranges from 10% to 20%, while topsoil of the farm ranges from 25- to 40-cm depth with an average bulk density of 1.35 g cm^{-3} (Brown et al., 2021; Hawes et al., 2018).

Field trials were conducted across 25 (6.25 × 1.5 m) plots in sandy loam soils over 2 years (from April 18, 2022, to September 16, 2022, and from March 27, 2023, to August 25, 2023) to evaluate barley-pea intercropping systems and their respective monocultures. Prior to the study, the plots were untilled and planted with cover crops (a mix of rye, vetch, triticale, fodder radish, brown mustard, buckwheat,



FIGURE 1 The study location (a) Balruddery Farm in the northeast of Scotland, UK; (b) Balruddery Farm and Mylnefield (UK Met Office) Station within Mylnefield-Invergowrie catchment; and (c) the experimental field and COSMOS Met Station (*Source*: Google Earth Pro).

TABLE 1 Overview of the cropping systems during the 2022 and 2023 spring crop cycles (April 18, 2022–September 16, 2022 and March 27, 2023–August 25, 2023).

Cropping systems	Sowing density (seeds m^{-2})	Mix ratio (%)
Barley (*Hordeum vulgare* L. 'Laureate'; BL) monoculture	360	NA
Barley (*Hordeum vulgare* L. 'KWS Sassy'; BS) monoculture	360	NA
Pea (*Pisum sativum* L. 'LG Stallion'; PS) monoculture	95	NA
BL and PS intercropping	252 (28.5)	70:30
BL and PS intercropping	252 (28.5)	70:30

Note: NA means not applicable; the number within a parenthesis is the sowing density for pea, while the one outside is for barley; the mix ratio is 70 and 30 for barley and pea, respectively.

and clover) for 3 years. The experiment in the second year was repeated with all treatments in the same plots as in the first-year trial to estimate trends in soil properties over multiple seasons. The trials involved five cropping systems, each with five replicates, arranged in a randomized block design (Figure S1). Cropping systems consisted of three monocultures and two barley-pea intercropping systems involving two barley cultivars and one pea cultivar (Table 1). Barley cultivars were (1) Laureate, a high-yielding barley cultivar (Hoad, 2019), and (2) KWS Sassy, a water stress-tolerant cultivar with abundant root hairs for efficient resource use under stressed conditions (Marin et al., 2021, 2022). The pea cultivar was LG Stallion, a high-yielding cultivar with good resistance to lodging at harvest (PGRO, 2020). The intercropping systems were sown as combined seed mixtures and replacement design with a mix ratio of 70% barley and 30% pea, similar to other trials (Karley et al., 2018; Pappagallo et al., 2021). Replacement design is where a certain proportion of one crop species is substituted by the other crop species, so both crops share the same total sowing density in the equivalent monoculture. A greater proportion of barley to pea was used because barley is the main crop due to its significant economic value, while pea is the secondary crop, primarily to provide soil N through biological fixation of atmospheric N. Guard plots of 1.5 m width were planted with a common barley cultivar around the experimental plots to reduce edge effects.

Each year, prior to sowing, conventional inversion tillage to 20-cm depth was performed on the field with a Kverneland four-furrow plough. The seedbed was prepared to 10- to 12-cm depth with a Kuhn power-harrow, and the seeds were drilled to 2- to 4-cm depth with a Gege plot drill. These were low input-systems with no applications of agrochemicals to the crops. Plots were harvested with a plot combine, and barley grain was dried to a moisture content of 14.5%. The plots were left uncropped between the years.

2.2 | Field data collection and environmental conditions of the study period

Soil was sampled on six occasions over the 2 years for analysis of the following soil parameters: total soil C and N, volumetric water content (VWC), water retention, dry bulk density, porosity, macroporosity, and penetration resistance, which are all key indicators of soil health (Yang et al., 2020). There were three sampling campaigns in 2022: pre-tillage (PT) on March 29, mid-season (MS) on June 28, and post-harvest (PH) on September 22; and an additional three in 2023: PT on February 21, MS on June 20, and PH on September 19 (Figure 2). The soil sampling was conducted before the soil cultivation and crop drilling (PT), during the growing season (MS), and after harvest (PH) to capture important soil management conditions and crop growth stages.

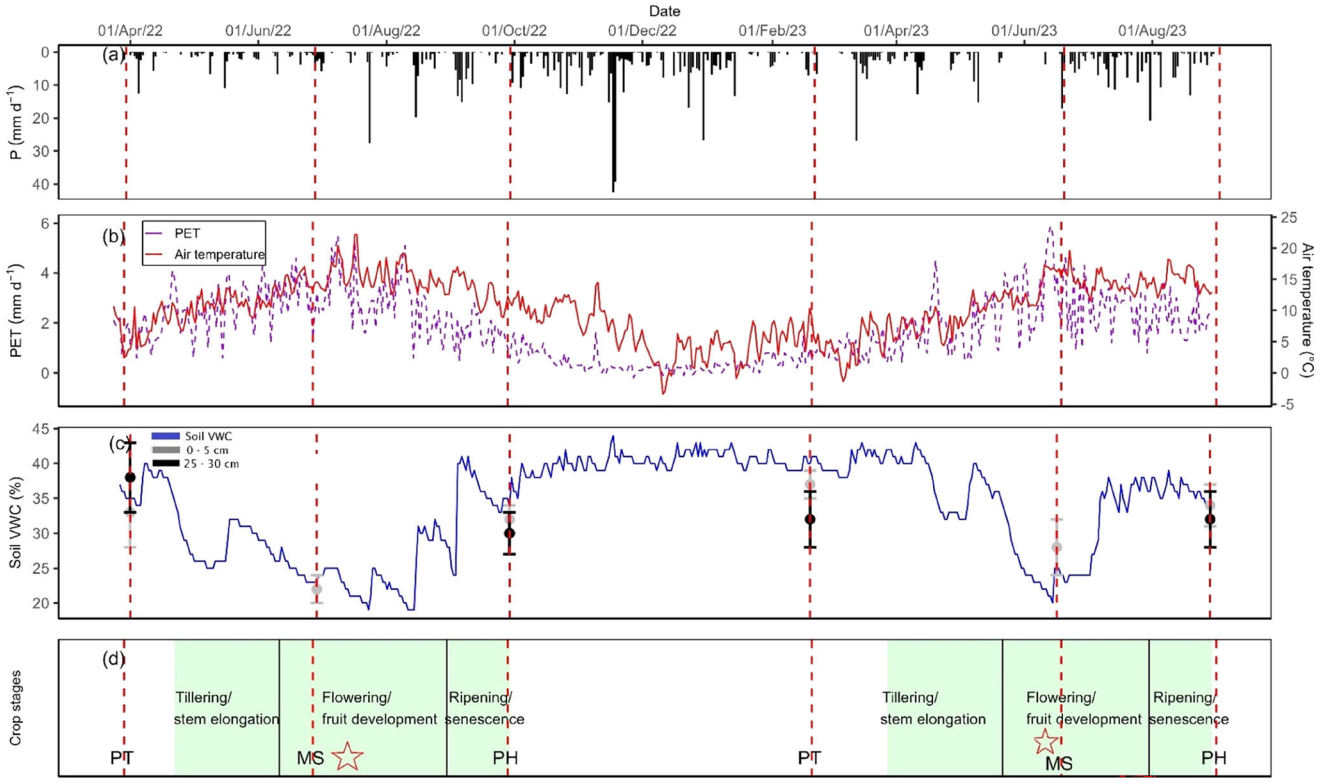


FIGURE 2 Hydro-climatological data during the study period. (a) Daily Precipitation amount (P, mm day^{-1}); (b) Air temperature and Potential Evapotranspiration (PET) estimated with weather station data and the Penman–Monteith equation; (c) Blue line represents daily soil volumetric water content (VWC) for the upper ~15-cm soil depth measured at the COSMOS Met Station. Gray and dark lines show means (± standard deviations) of soil VWC (core data) measured at upper topsoil (0–5 cm) and lower topsoil (25–30 cm), respectively, during the sampling occasions in the experimental field; (d) Phenological crop growth stages. The green bands represent the periods of each growth stage. Red star indicates pea senescence. The red dashed lines represent the soil sampling dates: pre-tillage (PT), mid-season (MS), and post-harvest (PH).

During each soil sample collection and for each plot, one cylindrical intact soil core (5.5 cm diameter and 4 cm height) and one bulk soil sample were randomly sampled from the upper topsoil (<5 cm) and lower topsoil (25–30 cm). During MS samplings, only upper topsoil samples were collected to avoid disturbing crops, and bulk soil samples for chemical analysis were excluded (Table S1). Weekly observations of crop phenological stages, including emergence, tillering, flowering, and maturity, were made to monitor crop development.

In addition, weather data and soil VWC (hereafter referred to as COSMOS data) were obtained from the COSMOS Met Station (56.482° N, 3.112° W; altitude 130 m; https://cosmos.ceh.ac.uk/sites/BALRD), near the experimental site (Figure 1). All data are presented at daily time intervals, although precipitation amounts were recorded at 1 min intervals, while average weather and soil VWC were recorded at 30 min intervals by data loggers in the field (Cooper et al., 2021; Smith et al., 2024). Daily potential evapotranspiration (PET) was estimated using the observed weather data and the Penman–Monteith equation (Allen et al., 1998). Also, the Mylnefield UK Met Office Station (56.456°N, 3.069°W; altitude 26 m) situated approximately 5.1 km southeast of the study site provided long-term daily climate records (1960–2021) for the Mylnefield-Invergowrie catchment.

In summary, 2022 was a particularly dry and warm year, while temperature and rainfall in 2023 were more typical (Durodola et al., 2025). The first season (April–September 2022) was drier (20% less rainfall) and warmer (+1°C) compared to the long-term average of this period (60 ± 34 mm, 12.2 ± 1°C). The second season (April–September 2023) had near-average rainfall but was colder (−0.7°C) than the long-term average (Table S2). In both years, the average daily air temperature showed a continual increase from 5°C in April to above 20°C, followed by a decline in August (Figure 2). Furthermore, soil VWC (COSMOS data) declined with precipitation in early spring, with the months of May–July 2022 and May–June 2023 being drier than the long-term average.

2.3 | Soil measurements

To determine soil physical properties, nylon mesh was attached to the base of the intact soil cores, which were first

weighed at field condition. Soil cores were saturated for at least 12 h, weighed, and then placed on ceramic suction plates for at least 10 days to equilibrate the soil to a matric potential of −50 kPa prior to reweighing to obtain water retention. Samples were then measured for soil penetration resistance with a universal test frame penetrometer (Instron model 5566; Instron) mounted with a 50-N load cell accurate to 2 mN at maximum load (Valentine et al., 2012). Each soil core was penetrated with a 1 mm diameter needle at 30° cone angle to a depth of 15 mm at 0.75 mm increments from the soil surface at a rate of 4 mm min^{-1}. Penetration resistance between 4.5 and 9.8 mm depth was averaged as the sample penetration resistance.

To determine bulk density (g cm^{-3}), the soil from the cores was reweighed after oven drying at 105°C for 24 h. Data are expressed as mass of oven-dried soil per volume of cylindrical core (Brown et al., 2021; Sala et al., 2000; Valentine et al., 2012). Soil water content was determined gravimetrically (g g^{-1}) as mass of water in the soil sample per mass of the oven-dried soil and converted to VWC (%) (hereafter referred to as core data) by using the bulk density of the soil sample. Porosity (%) was determined from bulk density, assuming 2.65 g cm^{-3} as particle density (Valentine et al., 2012). Thereafter, cores were sieved to 2 mm, and the mass of non-soil particles that did not pass the 2-mm sieve is regarded as the stone mass. Stone content (%) was estimated as the mass of the stones per total mass of the field moist sample.

Bulk soil samples were sieved using a 2-mm sieve, dried in an oven at 105°C for 24 h, and ball milled before using Dumas dry combustion procedure with a flash combustion elemental analyzer (model: NA 2500; manufacturer: Carlo Erba) to obtain total C concentration (g kg^{-1}) and total N concentration (g kg^{-1}) (Nelson & Sommers, 1996; Pella & Colombo, 1973). Soil C stock was estimated using the equivalent soil depth approach, with average bulk density across all cropping systems for each sampling, as bulk density was similar among systems per sampling occasion (Rovira et al., 2022; Wendt & Hauser, 2013). This approach allowed the C stock estimates to be compared across the cropping systems, ensuring that the observed dynamics in C stock are attributable to the cropping systems rather than to negligible variations found in bulk density per sampling occasion (Wendt & Hauser, 2013).

The C stock, C_{stock} (kg m^{-2}), was determined as given in Equation (1) (Brown et al., 2021):

$$C_{stock} = C_{conc} \times \rho_{soil} \times D_i \times 0.01 \quad (1)$$

where C_{conc} is the soil C concentration (g kg^{-1}) of each depth, ρ_{soil} is average soil dry bulk density (g cm^{-3}) of each depth, D_i is the depth of the soil layer (cm), and 0.01 is a unit conversion factor. Within-season change in soil C stock for each cropping system was estimated using Equation (2).

$$\Delta C_{stock} = C_{stock,PH} - C_{stock,PT} \quad (2)$$

where $C_{stock,PH}$ is the total C stock at the end of 2022 or 2023 and $C_{stock,PT}$ is the total C stock at the beginning of 2022 or 2023.

C stock adjusted for stone content (hereafter referred to as $C_{stock,adj}$) was estimated due to high stone content in the field site following Equation (3).

$$C_{stock,adj} = C_{conc} \times \rho_{fine\ soil} \times D_i \times \left(1 - p_{coarse}\right) \times 0.01 \quad (3)$$

where C_{conc} is the soil C concentration (g kg^{-1}) of each depth, $\rho_{fine\ soil}$ is average fine soil bulk density (g cm^{-3}) of each depth, D_i is the depth of the soil layer (cm), p_{coarse} is the coarse fraction (the average volumetric stone content, unitless), and 0.01 is a unit conversion factor. $\rho_{fine\ soil}$ was estimated by using only the mass and volume of fine soil (<2 mm particles) as follows: Equation (4):

$$\rho_{fine\ soil} = \left(M_{sample} - M_{coarse}\right) / \left(V_{sample} - \frac{M_{coarse}}{\rho_{coarse}}\right) \quad (4)$$

where $\rho_{fine\ soil}$ is the fine soil bulk density (adjusted for stone content), M_{sample} is the total mass of the core, M_{coarse} is the mass of stones (>2 mm), V_{sample} is the total volume of the core and ρ_{coarse} is the density of stones (2.65 g cm^{-3}).

The difference in a soil property between an intercropping system and its respective monoculture per sampling, ΔX, was used to determine the impact of intercropping, as shown in Equation (5).

$$\Delta X = X_i - X_m \quad (5)$$

where X_i and X_m are the values of an intercropping and its respective monoculture for a given soil property, respectively.

2.4 | Yield and grain analysis

The plot barley grain yield (g m^{-2}), adjusted to moisture content of 14.5%, was estimated using the plot combine as the mass of the grain obtained per plot area at harvest. Moisture content adjustment was not applied to peas since there were no harvestable yields in either intercropping or monoculture. Crop productivity in intercropping was expressed as net effect, NE (g m^{-2}), which is defined as the difference in grain yield between the observed intercropping yield and the expected yield based on the observed monoculture yield and crop species proportions (Li et al., 2020; Loreau & Hector, 2001). It was calculated following Equation (6) (Li

et al., 2020; Loreau & Hector, 2001).

$$\mathrm{NE} = \left(Y_{i,1} + Y_{i,2}\right) - \left(Z_1 Y_{m,1} + Z_2 Y_{m,2}\right) \quad (6)$$

where $Y_{i,1}$ and $Y_{i,2}$ are the intercrop yields of component crop species 1 and 2, respectively (g m^{-2}), $Y_{m,1}$ and $Y_{m,2}$ are monoculture crop yields (g m^{-2}), and Z_1 and Z_2 are the proportions of barley and pea, respectively ($Z_1 = 0.7, Z_2 = 0.3$) in the intercropping based on mix ratio (%) of sowing densities (seeds m^{-2}). Positive values of NE indicates absolute yield gain and shows that intercropping is more productive than when crops are grown separately at similar densities in a monoculture.

Land productivity was expressed as the land equivalent ratio (LER), following Equation (7), indicating the area of land needed to produce the yields in a unit area of intercropping using corresponding monoculture yields (Mead & Willey, 1980; Stomph et al., 2020):

$$\mathrm{LER} = \frac{Y_{i,1}}{Y_{m,1}} + \frac{Y_{i,2}}{Y_{m,2}} = p\mathrm{LER}_1 + p\mathrm{LER}_2 \quad (7)$$

where $p\mathrm{LER}_{1,2}$ are the corresponding relative yields also referred to as partial LER. LER is a unitless value which, when >1, signifies that land resources are more effectively used by intercrops than by each crop as a monoculture. Since peas had no harvestable yields in either intercropping or monoculture, only *p*LER of barley is reported (see more details in Section 3.2).

To determine the grain yield quality, 200 g of harvested grains from each plot were cleaned and ball milled to obtain total N and C concentration. Total C (g kg^{-1}) and total N (g kg^{-1}) of the grains were then measured using the same method as for soil C and N, as described in section 2.3.

2.5 | Statistical analyses

Statistical analyses were performed in R (v4.2.2) (R Core Team, 2022). Linear mixed-effects models with Restricted Maximum Likelihood (REML) estimation for repeated measurements were conducted using *lme4* package (Bates et al., 2015) to analyze the effects and interactions of cropping system, sampling, and soil depth for each soil property. Plots were set as a random effect for each soil property. An *F*-test for homogeneity of variance was conducted for each soil property across the 2 years to determine whether the data could be pooled for combined analysis or should be analyzed separately by year. All soil parameters indicated significant differences in variances ($p < 0.05$) except bulk density, indicating separate year analysis is appropriate (Table S3). Hence, each year was analyzed separately. This approach is also justified since soil properties would change more noticeably in response to treatment in the second year, as management impacts on soil can occur in the short term or can take longer than 1 year to develop (Sandén et al., 2018). For grain nutrient concentration, separate linear mixed-effects models with REML estimation were used to assess the main effects of cropping system and year, also including plots as a random effect. Pairwise comparisons of estimated marginal means were performed in *emmeans* (Lenth, 2022), with *p*-values adjusted using Tukey's method to account for comparisons between an intercropping system and its monoculture. Prior to analyses, the normality of data was tested with the Shapiro–Wilk test. Penetration resistance data, which were non-normal data, were log transformed. Log-transformed data distributions were normal and are reported. Results were considered significant at *p*-value ≤ 0.05 and marginal at *p*-value < 0.1.

3 | RESULTS

3.1 | Variations in soil properties

High initial soil C and N concentrations and soil compaction were observed at the beginning of the study, with uniform distribution across plots (Tables S4a and S5a). Overall, soil C and N concentrations significantly decreased by the 2022 post-harvest sampling following tillage and plant growth (Table S4a). However, this returned to initial levels by the end of the study. Also, $C_{\mathrm{stock,adj}}$ was generally lower than C stock.

In the first year, total C and C stock varied significantly along the soil profile, with most variation in time found in the upper topsoil (Table S4a). Within this period, mean total C was higher in the upper topsoil (24.5 ± 2.5 g kg^{-1}) than the lower topsoil (23.9 ± 1.6 g kg^{-1}), while mean total C stock was reduced in the upper (1.71 ± 0.18 kg m^{-2}) compared to the lower topsoil (1.86 ± 0.12 kg m^{-2}). $C_{\mathrm{stock,adj}}$ was similar in the upper (1.46 ± 0.07 kg m^{-2}) to the lower topsoil (1.42 ± 0.08 kg m^{-2}). By the second year, total C stabilized with depth, while C stock showed significant difference. For this time, mean total C was 24.1 ± 1.1 g kg^{-1} and 24.5 ± 1.2 g kg^{-1} in the upper and lower topsoil, respectively, while mean total C stock was 1.73 ± 0.10 and 1.95 ± 0.09 kg m^{-2} in the upper and lower topsoil, respectively. $C_{\mathrm{stock,adj}}$ was 1.24 ± 0.05 kg m^{-2} across both depths. Mean soil N was relatively unchanged with depth, with 2.23 ± 0.2 and 2.24 ± 0.2 g kg^{-1} in the upper and lower topsoil, respectively (Table S4).

In addition, apart from penetration resistance, other soil physical properties mostly showed significant variation with depth, and most variation in time was found in the upper topsoil (Table S5). Mean penetration resistance was 1.62 ± 1.32 and 1.96 ± 1.45 MPa, and mean bulk density was 1.28 ± 0.15 and 1.39 ± 0.20 g cm^{-3} in the upper and lower topsoil, respectively. Soil VWC (core data), water retention (VWC at −50 kPa), and porosity mostly varied with environmental conditions, showing lower soil matric potential and larger

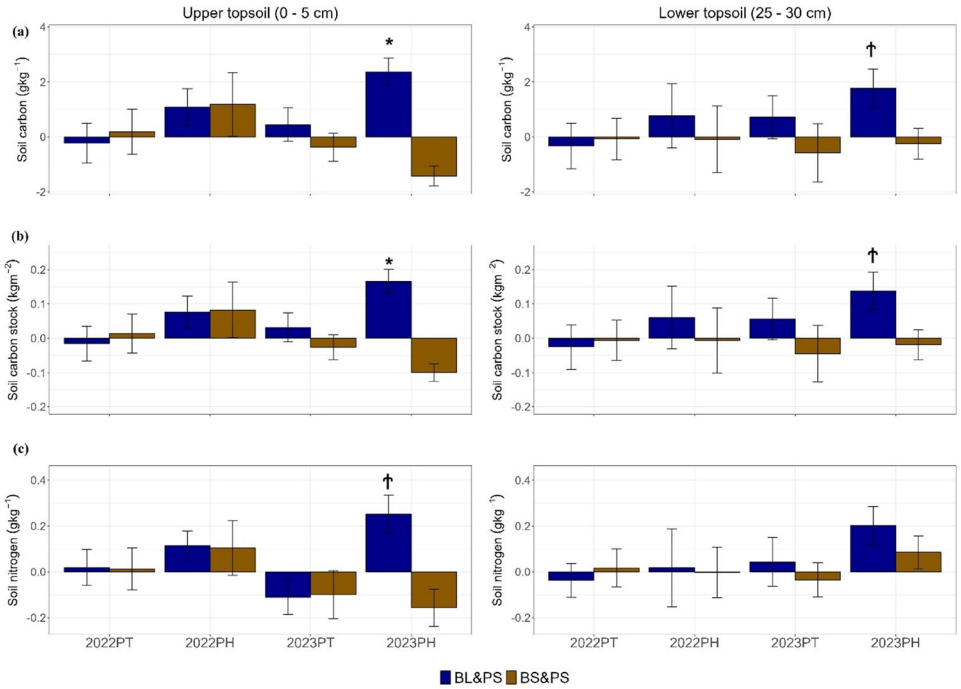


FIGURE 3 Comparative differences in chemical properties: (a) total carbon concentration (g kg^{-1}); (b) total carbon stock (kg m^{-2}); and (c) total nitrogen (g kg^{-1}) of intercropping systems and their respective monocultures during all sampling occasions. * and † indicate significant ($p < 0.05$) and marginal ($p < 0.1$) differences, respectively, between an intercropping and its monoculture. Bars indicate standard error. BL & PS = Barley (Laureate) intercropping with pea; BS & PS = Barley (KWS Sassy) intercropping with pea.

soil pores during the MS samplings. Soil VWC (core data) in the upper topsoil ranged from 17% to 43%, with the lowest sampling mean of 22% observed during the 2022 MS, which was a drought year, while the lower topsoil ranged from 24% to 51% (Table S5). Meanwhile, water retention in the upper topsoil ranged from 9% to 39%, with the lowest sampling mean of 15% observed during the 2023 MS, while the lower topsoil ranged from 17% to 48%. Mean porosity was 52 ± 6% and 47 ± 8% in the upper and lower topsoil, respectively, with a lower mean of 47% in both depths during the PT period. Mean stone content was found to be relatively similar with time, with 11% and 12% in the upper and lower topsoil, respectively.

3.2 | Soil properties of intercropping in comparison with their respective monocultures

In the first year, soil C and other properties were similar in intercrops and monocultures in the upper and lower topsoil depths (Figure 3; Figure S2), and the effect of cropping systems on C ($p = 0.065$), C stock ($p = 0.074$), and $C_{stock,adj}$ ($p = 0.079$) was not statistically significant in the second year (Table S4b). Other soil properties were also unaffected across both study years (Tables S4 and S5). However, the post-harvest samples in the second year of the high-yielding barley cultivar, Laureate, showed significantly higher total C concentration, C stock, and $C_{stock,adj}$ in the upper topsoil in intercropping compared to its monoculture (Table 2). This was not observed separately for the stress-tolerant barley cultivar, KWS Sassy (Table 2; Figure 3). For Laureate, the intercropping system showed an 8.1% increase in total C (25.5 vs. 23.6 g kg^{-1}), a 6.0% higher C stock (1.77 vs. 1.67 kg m^{-2}) and a 9.8% higher $C_{stock,adj}$ (1.12 vs. 1.23 kg m^{-2}) in the upper topsoil at the 2023 post-harvest sampling (Figure 3; Table 2). A residual effect was also noted in the lower topsoil, with a non-significant trend toward increased total soil C ($p = 0.094$) and C stock ($p = 0.075$) observed in barley (Laureate) intercropping compared with its monoculture (Figure 3).

Within-season changes of soil C stock in each year of the intercropping systems were similar to or higher than their respective barley monocultures (Table 3). Specifically, the high-yielding barley (Laureate) intercropping system stored higher C stock than its monoculture at both soil depths across the 2 years. In contrast, intercropping the stress-tolerant barley (KWS Sassy) exhibited inconsistent results, showing higher seasonal C stock only in the upper topsoil in the first year and decreased levels in the lower topsoil in the second year compared to its monoculture (Table 3).

Notably, by the second year, a marginal increase in total N ($p = 0.075$) was observed in the upper topsoil of intercropping of the high-yielding barley (Laureate) compared with its monoculture at the 2023 post-harvest sampling (Figure 3).

TABLE 2 Field data values of soil carbon concentration (g kg^{-1}), carbon stock (kg m^{-2}), carbon stock (stone adjusted) (kg m^{-2}), and nitrogen (g kg^{-1}) in 2023 at 2 depths (0–5 and 25–30 cm) for all the cropping systems during the post-harvest (PH) soil sampling.

		2023			
Cropping systems	Depth (cm)	Carbon concentration (g kg^{-1})	Carbon stock (kg m^{-2})	Carbon stock (stone adjusted) (kg m^{-2})	Nitrogen concentration (g kg^{-1})
BL	0–5	23.6 ± 0.9^{a}	1.67 ± 0.07^{a}	1.12 ± 0.04^{a}	2.13 ± 0.2^{ab}
BL & PS	0–5	25.5 ± 1.0^{b}	1.77 ± 0.10^{b}	1.23 ± 0.04^{b}	2.34 ± 0.1^{b}
BS	0–5	25.0 ± 0.3^{ab}	1.75 ± 0.02^{ab}	1.19 ± 0.01^{ab}	2.55 ± 0.1^{ab}
BS & PS	0–5	23.6 ± 0.8^{a}	1.65 ± 0.05^{a}	1.12 ± 0.04^{a}	2.10 ± 0.2^{a}
PS	0–5	23.7 ± 1.9^{a}	1.66 ± 0.13^{ab}	1.13 ± 0.09^{ab}	2.14 ± 0.3^{ab}
BL	25–30	23.5 ± 1.1^{a}	1.84 ± 0.08^{a}	1.16 ± 0.05^{a}	2.13 ± 0.1^{a}
BL & PS	25–30	25.3 ± 1.2^{a}	1.98 ± 0.09^{a}	1.25 ± 0.06^{a}	2.33 ± 0.2^{a}
BS	25–30	24.7 ± 1.1^{a}	1.93 ± 0.09^{a}	1.22 ± 0.05^{a}	2.23 ± 0.2^{a}
BS & PS	25–30	24.5 ± 0.6^{a}	1.91 ± 0.05^{a}	1.21 ± 0.03^{a}	2.31 ± 0.0^{a}
PS	25–30	24.7 ± 1.4^{a}	1.93 ± 0.11^{a}	1.22 ± 0.07^{a}	2.32 ± 0.2^{a}

Note: Data are the mean ± standard deviation of five replicates. BL = Barley (Laureate) monoculture; BL & PS = Barley (Laureate) intercropping with pea; BS = Barley (KWS Sassy) monoculture; BS & PS = Barley (KWS Sassy) intercropping with pea; PS = Pea monoculture. No shared letters denote a pairwise significant difference between cropping systems ($p < 0.05$) using Tukey's method.

TABLE 3 Comparative differences in seasonal changes of carbon stock (g C m^{-2}) of the intercropping systems compared with the respective barley monocultures.

Cropping systems	Upper topsoil (0–5 cm)		Lower topsoil (25–30 cm)	
	2022	2023	2022	2023
BL & PS	92	135	86	82
BS & PS	69	−73	0	26

Note: BL & PS = Barley (Laureate) intercropping with pea; BS & PS = Barley (KWS Sassy) intercropping with pea.

TABLE 4 Data values of barley grain yields of the cropping systems.

	2022	2023
Cropping systems	Yield (g m^{-2})	Yield (g m^{-2})
BL	440 ± 40	320 ± 60
BL & PS	440 ± 50	350 ± 60
BS	410 ± 50	300 ± 60
BS & PS	380 ± 60	300 ± 40

Note: BL = Barley (Laureate) monoculture; BL & PS = Barley (Laureate) intercropping with pea; BS = Barley (KWS Sassy) monoculture; BS & PS = Barley (KWS Sassy) intercropping with pea. Data are the mean ± standard deviation of five replicates. Sowing rate of barley in intercropping is 70 % of monocultures.

There were limited effects of intercropping on physical properties along the soil profile across both years (Figure S2).

3.3 | Yield, productivity, and grain nutrient concentration of intercropping systems

Overall, intercropping at least maintained or increased barley yields in both years compared with their respective monocultures, with some cultivar-specific differences (Table 4). Despite the barley being sown at 70% of the monoculture sowing rate, the yield in the high-yielding Laureate intercropping was 100% and 110% of its monocrop yield in 2022 and 2023, respectively, while in the stress-tolerant KWS Sassy, the yield for intercropping was 94% and 100% of its monocrop yield during these times (Table 4). These comparatively higher yields of intercropping systems for the high-yielding cultivar were achieved with 30% fewer barley seeds sown. There was no harvestable yield of peas in both the intercropping and pea monoculture systems, as the peas reached senescence MS during the two study years (Figure 2). Nevertheless, the peas germinated and grew until MS (~80 days after sowing) in both years of the study, providing substantial period of co-growth of barley and peas in intercropping. Notably, barley yields were higher in 2022 than 2023, and cultivar Laureate generally had higher yields than KWS Sassy.

Over the 2 years, both barley cultivars in intercropping systems exhibited absolute yield gains compared to their monocultures. Overall yield gain (NE) in intercropping was 90–132 g m^{-2}, while partial land equivalent ratio (pLER) improved by up to 10%, demonstrating enhanced crop and land productivity in the intercropping systems (Figure 4).

Cropping systems significantly affected barley grain C ($p < 0.05$) and marginally influenced N ($p = 0.08$) concentrations, with significant variations across the 2 years (Table 5). Notably, barley grain nutrient concentrations were higher in 2022 than 2023. In 2023, intercropping KWS Sassy showed a significantly higher grain C concentration (408 ± 6 g kg^{-1}), which was 5.7% greater than its monoculture (386 ± 19 g kg^{-1}) (Figure 5). Similarly, intercropping Laureate demonstrated a marginally higher grain C concentration compared

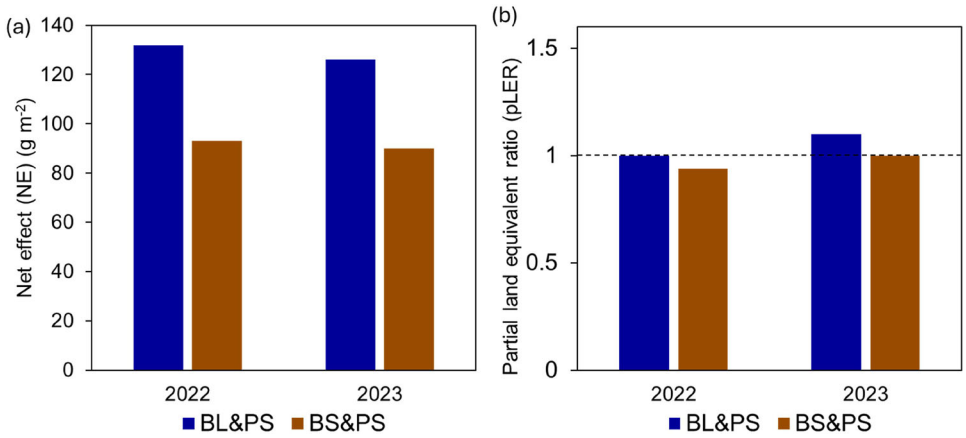


FIGURE 4 Productivity of intercropping systems. (a) Net effect (NE) (g m^{-2}) and (b) partial land equivalent ratio (pLER) of barley. BL & PS = Barley (Laureate) intercropping with pea; BS & PS = Barley (KWS Sassy) intercropping with pea. Number of replicates ($n = 5$). The dashed line at 1 indicates monoculture performance.

TABLE 5 Data values of barley grain nutrient concentrations.

	C (g kg^{-1})		N (g kg^{-1})	
Cropping systems	**2022**	**2023**	**2022**	**2023**
BL	409 ± 5[a]	395 ± 5[a]	10.9 ± 1.2[a]	8.8 ± 0.4[a]
BL & PS	410 ± 4[a]	408 ± 4[a]	11.8 ± 1.1[a]	9.4 ± 0.9[a]
BS	407 ± 8[a]	386 ± 19[b]	11.8 ± 0.8[a]	9.2 ± 0.8[a]
BS & PS	406 ± 6[a]	408 ± 6[a]	12.1 ± 0.4[a]	9.5 ± 0.3[a]
Cropping system	0.0086*		0.0825†	
Year	0.0028*		<0.001*	
Cropping system × year	0.0189*		0.8619	

Note: Data are the mean ± standard deviation of five replicates, with differences between cropping systems, years, and their interaction established using REML for repeated measurements from which the *p*-value data are derived. * and † indicate significant ($p < 0.05$) and marginal ($p < 0.1$) differences, respectively. BL = Barley (Laureate) monoculture; BL & PS = Barley (Laureate) intercropping with pea; BS = Barley (KWS Sassy) monoculture; BS & PS = Barley (KWS Sassy) intercropping with pea. No shared letters denote a pairwise significant difference between cropping systems ($p < 0.05$) using Tukey's method.

to its monoculture ($p = 0.089$). These differences were not observed in 2022. In contrast, grain N concentration remained similar for intercropping barley and their monocultures in both years.

4 | DISCUSSION

This study revealed varied and cultivar-dependent effects of barley-pea intercropping on total soil C concentration and C stock, alongside higher yield gains, enhanced crop and land production, and higher grain nutrient concentration with no agrochemical inputs. These results were achieved despite there being no harvestable pea crop. In addition, barley cultivar-specific responses were observed. The following discussion will examine the dynamics of soil C under low agrochemical inputs, explore the possible mechanisms underlying the observed benefits of intercropping, and assess the role of cultivar traits in maximizing these benefits.

4.1 | Short-term effects of intercropping on soil carbon

The high initial soil C and N concentrations and soil compaction observed at the beginning of the 2022 growing season can be attributed to the field being untilled and planted with cover crops for 3 years prior to the study (Blanco-Canqui et al., 2015). Overall, soil C declined in all the cropping systems from the first to the second study year, likely due to initially high N and C levels before land preparation and cultivation. Also, soil properties mostly varied in depth, with most temporal changes in the upper topsoil, reflecting pronounced effects of plant-soil interactions, management practices, and biological processes in the shallower layers in temperate agroecosystems (Geris et al., 2021; Haddaway et al., 2017). It was observed that total C concentration and C stock varied significantly between the upper and lower topsoil, with most temporal variation in the upper topsoil, consistent with organic systems where increases in soil C occurred over the

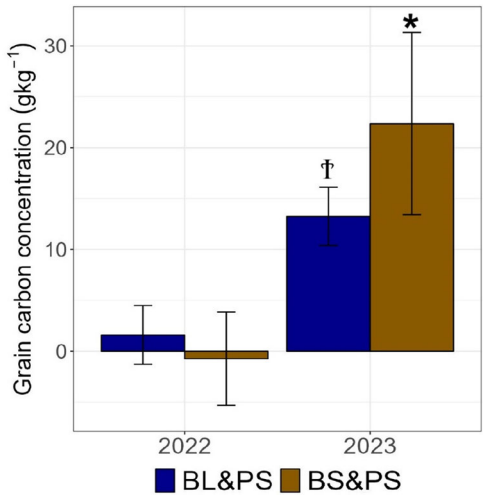


FIGURE 5 Comparative differences in barley grain nutrient concentration of carbon concentration (g kg^{-1}) of intercropping systems and their respective monocultures. * and † indicate significant ($p < 0.05$) and marginal ($p < 0.1$) differences, respectively, between an intercropping and its monoculture. Bars indicate standard error. BL & PS = Barley (Laureate) intercropping with pea; BS & PS = Barley (KWS Sassy) intercropping with pea.

long term in the topsoil (Gattinger et al., 2012). Total C was observed to stabilize with depth, while C stock varied, likely due to increasing bulk density with depth and reduced inputs with slower decomposition rates (Rovira et al., 2022; Stockmann et al., 2013). (Stockmann et al., 2013).

While the high-yielding barley increased total soil C concentration and C stock when intercropped compared to its monoculture in the short term (i.e., after 2 years), other soil properties were mostly unaffected. This may not be surprising, given that long-term research on intercropping and cover cropping has indicated that substantial changes in soil structure typically require several years to take effect (Dung et al., 2022; Gongora et al., 2022; Yang et al., 2023). The field used in this study was tilled between cropping years, which is likely to contribute to the lack of detectable impact on soil physical properties between cropping systems.

The increase in total soil C concentration and C stock under the high-yielding barley intercrop was limited to the upper topsoil (<5-cm depth), aligning with Li et al. (2024), who highlighted in a global review of intercropping systems the importance of soil depth and crop/cultivar selection in C sequestration in these systems. Similarly, the observations align with the study of Chapagain and Riseman (2014a), who found an increase in C sequestration in barley-pea intercrops in the short term in an organic temperate agroecosystem. However, the results contrast with several long-term studies on cereal-legume combinations and cover cropping that suggest soil C requires several years to accumulate (Dung et al., 2022; Oelbermann et al., 2015; Wang et al., 2014). It also contrasts the finding of Brooker et al. (2024b) in a Scottish-based study that soil C was reduced in different crop mixtures in the top 10-cm soil depth. These different responses could be associated with differences in crop/cultivar, climate, and management practices of these studies, which play key roles in maximizing the benefits of intercropping (Brooker et al., 2024a; Li et al., 2020).

The observed increase in soil C found only in barley (Laureate) intercropping compared to its monoculture may be attributed to relatively more enhanced aboveground biomass production. Higher yields and crop productivity of this cultivar in the intercropping system are likely to have resulted in greater crop residue returning to the soil. The subsequent incorporation of this biomass through tillage could have significantly contributed to the observed increase in soil C levels (Yang et al., 2023). This is supported by previous findings that crop residue retention enhances soil organic matter through plant material decomposition, thereby improving soil C stocks (Hu et al., 2017; Yu et al., 2022). Furthermore, increased soil C could also be related to enhanced root biomass from the combined crops in the upper topsoil, even with the early-season presence of peas in the intercropping systems. This enhanced root biomass could have accelerated C accumulation in the short term (Homulle et al., 2021; Li et al., 2023). Moreover, intercropping promotes diverse microbial communities that enhance nutrient availability and cycling (Liu et al., 2024), leading to improved soil fertility and potentially reducing the need for synthetic fertilizers, especially in low agrochemical input management systems. Also, root exudation in intercrops may further stimulate microbial activity and contribute to carbon inputs, nutrient cycling, and plant growth (Zhang et al., 2024).

Within-season changes in C stock were found to be higher in intercropping systems than in barley monocultures, particularly with the high-yielding barley (Laureate). Notably, a trend toward increased total soil C concentration and C stock (lower topsoil) and N (upper topsoil) was observed in Laureate barley intercrops compared with its monoculture, indicating potential long-term benefits of this intercropping system. Again, while significant effects in deeper soil layers may require long-term research (Yang et al., 2023), the improved C levels in upper topsoil and nutrient availability can lead to higher crop yields and reduced input costs. This offers immediate soil health benefits to farmers adopting intercropping practices while enhancing environmental sustainability (Glaze-Corcoran et al., 2020).

This study found that failing to adjust C stock by stone content resulted in overestimation of C stock, consistent with Brown et al. (2021) and Fenton et al. (2024). The presence of coarse fractions can distort C stock estimates, yet many studies neglect this factor (Brown et al., 2021). These findings emphasize the need to consider stone content in soil

C assessments for accurate estimations and comparability (Brown et al., 2021; Schrumpf et al., 2011).

4.2 | Yield and productivity advantages of intercropping

The finding that intercropping resulted in yield gains of approximately 90–132 g m^{-2} (~34%–58% higher than monoculture yields) compared to monocultures aligns with the approximately 20% higher yield observed in another Scottish-based study (Brooker et al., 2024b) and averages of 30% increases found across Europe (Brooker et al., 2024a) using crop performance ratio as a metric. In terms of land productivity, a higher pLER of up to 10% was found in intercropping, similar to other studies in temperate and non-temperate agroecosystems (Li et al., 2020; Stomph et al., 2020). Higher land productivity observed indicates that less land is needed to produce the combined yield of intercrop components compared to growing them separately in monocultures at similar densities (Li et al., 2023). The drought that occurred in 2022 in Scotland, coupled with higher temperatures (Figure 2; Table S2) provided a unique opportunity to evaluate the performance of intercropping under water-stressed conditions. Notably, even under water stress, intercropping maintained yields and productivity, despite early senescence of the pea intercrop, indicating the potential resilience of these systems to changing climate-induced drought periods (Huss et al., 2022).

Grain C content in intercropped barley (KWS Sassy) was higher than in monoculture, aligning with the findings of Chapagain and Riseman (2014a) but contradicting Brooker et al. (2024b), who reported no difference in intercropped barley but higher grain C and N content in intercropped wheat. This discrepancy may be attributed to the different cultivar traits used across studies.

The early senescence of the pea crop observed in both intercropping and monoculture plots during mid-seasons could be related to the extensive and unusual water stress conditions from April to August in 2022 and April to June in 2023, coupled with extreme temperatures in 2022 (Table S2). A similar study by Sears et al. (2021) revealed that legume crops, peas, and faba beans yielded poorly in monocultures with no harvestable yields in intercropping plots due to the 2018 drought and extreme temperatures in Denmark and most of Europe. Legumes are found to be generally less drought resistant than cereals (Daryanto et al., 2017). Given that extreme weather events are projected to be more frequent due to climate change (IPCC, 2023), innovative crop mixtures such as mixtures of different cultivars, cereal, and multiple legumes with different drought/wet tolerance traits could become increasingly important in mitigating the impacts of these stresses on crop production and yield stability.

Increased yield and productivity observed in intercropping could be attributed to several mechanisms. First, the early season presence of peas and substantial overlapping growth with barley possibly provided N fixation, boosting barley early in its development and allowing it to close the yield gap despite lower sowing rate compared with monocultures (Li et al., 2020; Rodriguez et al., 2020; Yu et al., 2022). Also, it could be due to facilitation leading to enhanced nutrient uptake by barley, using nutrients in its early development growth stage to effectively accumulate biomass both aboveground and belowground (Duchene et al., 2017). Translocation of nutrients from barley tissues to grain during maturity is another possible mechanism (Brooker et al., 2015; Rogers et al., 2019), as indicated by higher grain nutrient content of intercropping barley observed in this study. Although not covered in this study, the possible reduction in disease and pest pressure in intercropping systems may have also contributed to the observed yields and productivity benefits (Stomph et al., 2020). It is also possible that increased tillering contributed to the yield advantage. However, it is arguable that increased tillering would only bring intercrop yield to the level of the monocrop, since both crops exploited the available resource space up to their carrying capacity (Huss et al., 2022; Stomph et al., 2020). Thus, the observed yield advantage above the monocrop is attributable to the improved soil conditions created by the early co-growth of pea during barley establishment, even though the peas did not have any harvestable yields.

4.3 | The role of cultivar (genotypic) traits in maximizing benefits of intercropping

The findings of this study demonstrated that cultivar or genotypic traits influence the benefits of intercropping, supporting previous research that the positive effects of intercropping depend on crop and/or cultivar trait combination (Brooker et al., 2024a; Homulle et al., 2021; Li et al., 2021). For instance, Laureate exhibited higher crop productivity in intercropping than KWS Sassy across both years, attributable to its high-yielding traits (Hoad, 2019). The differences in cultivar yields could be due to phenotypic plasticity in the absence of competition from peas (Homulle et al., 2021; Pigliucci, 2001). Laureate intercropping possibly exhibited more plasticity in terms of extensive tillering (not measured), leading to more of the aboveground space being filled and enhanced aboveground biomass production (Huss et al., 2022). Hence, despite lower sowing rates, it had similar or higher yields than all other systems, including monocultures, suggesting potential yield advantages for certain barley genotypic/cultivar traits in mixtures.

Recent studies reveal that cultivars with certain traits can optimize resource use (e.g., water and nutrients) and productivity in intercropping systems through complemen-

tary interactions (Durodola et al., 2025; George et al., 2022). Also, some cultivars perform better under specific environmental stresses (e.g., drought or nutrient deficiency) (Brooker et al., 2021; Marin et al., 2022), which could be more pronounced in intercropping. In this study, the stress-tolerant KWS Sassy generally showed higher grain N contents than Laureate, and intercropped KWS Sassy exhibited higher grain C content than its monoculture. This indicates better nutrient uptake performance for the stress-tolerant KWS Sassy, which was more pronounced in intercropping systems and could be attributable to the cultivar's root hair traits that facilitate efficient resource use during environmental stresses (Marin et al., 2021). KWS Sassy in intercropping systems also demonstrated remarkable flexibility, more than Laureate, in water uptake from deeper sources across a range of environmental conditions (Durodola et al., 2025). Interestingly, intercropping with Laureate showed the highest soil C accumulation among all cropping systems in the second year, while in contrast, KWS Sassy intercrops did not affect soil C. These results underline the importance of targeted cultivar selection tailored to local conditions and specific goals to maximize the benefits of crop mixtures. The findings highlight the potential for targeted breeding of cultivars with desirable traits for sustainable and beneficial intercropping systems while adapting to changing environmental conditions (Haug et al., 2023).

Overall, the findings of this study supported the hypotheses that (1) barley-pea intercropping at least maintained or increased soil C, crop productivity, and grain nutrient content compared to monocultures, and (2) barley cultivar traits affected the impacts of barley-pea intercropping on soil carbon and crop performance. This study revealed for the first time in a temperate agroecosystem significant increase in total soil C and C stock in barley-pea intercrops compared to monoculture, alongside yield gains, enhanced crop and land production, and higher grain nitrogen content with no agrochemical inputs.

4.4 | Limitations and opportunities for future research

It is acknowledged that early pea senescence in the intercropping systems shortened the barley-pea co-growth period across both study years. This premature senescence is likely to have limited the potential benefits of intercropping on soil C and overall productivity in this study. Extended co-growth periods could have provided more significant improvements in soil properties and potentially higher crop and land productivity than observed in this study (Huss et al., 2022). Also, this study's 2-year duration was not long enough to detect any substantial soil structure improvements, which typically require several years to develop (Oelbermann et al., 2015; Sandén et al., 2018). This indicates the need for longer-term field experiments that could potentially reveal bigger effects of intercropping on soil C, structure, and overall productivity (George et al., 2014; Yang et al., 2023).

Long-term studies can be prohibitively expensive, but another approach for studying long-term implications of different intercropping systems could be to use process-based models. This study provides the basic dataset to develop models for exploring the resilience and long-term sustainability of different intercropping systems under future climate scenarios (Begum et al., 2022; Gaudio et al., 2019). Process-based modeling approaches informed by short-term data can then be used to project the attainable soil C sequestration and characterization of soil water and C cycling in these systems over the long term. The outcomes of such modeling exercises would provide indications of the potential of different intercropping systems as a viable climate change adaptation and mitigation measure. While low-input intercropping systems offer potential benefits in terms of reducing carbon footprint, their feasibility in commercial farming could be challenging (Brannan et al., 2023). Commercial farming, often characterized by high inputs, usually achieves significantly higher yields due to fertilizer applications. Further research is therefore needed to explore the scalability and feasibility of low-input intercropping systems in commercial farming settings to ensure a balanced approach that integrates the multiple benefits of low-input intercropping with commercial farming. Finally, future research could explore more cultivar or genotypic traits in intercropping systems to aid crop breeding for optimal benefits of crop mixtures (Haug et al., 2023; Kiær et al., 2022).

5 | CONCLUSIONS

This study assessed soil C and crop production in two barley cultivars with contrasting phenotypic traits (high-yielding cultivar Laureate and water stress-tolerant KWS Sassy) intercropped with pea versus their respective monoculture systems over 2 years of cultivation with no agrochemical inputs in a temperate agroecosystem. Despite the peas having had no harvestable yields in either intercrop or monoculture systems due to water stress, the intercropped barley produced higher yield gains and land productivity and better grain quality than barley monocultures. Barley cultivar-specific responses to intercropping were also observed, with more pronounced positive effects for the high-yielding cultivar Laureate than the water stress-tolerant KWS Sassy. Intercropping had no impacts on soil C in the first year for either cultivar. By the second year, the Laureate intercropping system showed significant increase in total soil C concentration and C stock in the upper topsoil, although other soil properties remained similar. Overall, intercropping at least maintained or increased C and other measured variables. The findings suggest that barley-pea intercropping could be a promising strategy for

providing insurance against complete crop failure, maintaining yields, enhancing soil C, and effectively supporting soil health, but it is dependent on barley cultivar traits. This study has shown for the first time the opportunities for positive effects of intercropping in low-input systems on soil C in temperate agroecosystems, underscoring its potential for adaptation to and mitigation of climate change.

AUTHOR CONTRIBUTIONS

Oludare S. Durodola: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; visualization; writing—original draft; writing—review and editing. **Kirsty Binnie**: Investigation; methodology; resources; writing—review and editing. **Cathy Hawes**: Conceptualization; funding acquisition; investigation; methodology; resources; supervision; writing—review and editing. **Jo Smith**: Conceptualization; funding acquisition; investigation; methodology; resources; supervision; writing—review and editing. **Tracy A. Valentine**: Conceptualization; funding acquisition; investigation; methodology; resources; supervision; writing—review and editing. **Josie Geris**: Conceptualization; data curation; funding acquisition; investigation; methodology; project administration; resources; supervision; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data generated and analyzed during this study are publicly available to download from Durodola et al. (2026) available at https://doi.org/10.5281/zenodo.18158238.

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SUPPORTING INFORMATION

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