



Proficiency of green fallow compared to bare fallow, grain legume and cereal pre-crops in a long-term crop rotation

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ABSTRACT

Long-term experiments (LTEs) are an important tool to investigate the effects of crop rotation and fertilization measures under climate change conditions. However, LTEs that integrate fallow management strategies, including green and bare fallow are hardly available in Europe today. The objective of our study is to explore how the integration of green and bare fallow, grain legume and cereal crops in long-term experiments enhances ecosystem resilience under changing climate conditions, to better understand their contributions to sustainable agricultural practices. Therefore, a LTE established in 1982 aimed to study the role of fallow lands (green vs. bare), grain legume and cereal pre-crops on the yields of subsequent cereal crops. The study was conducted within a rotational cropping system and evaluated after at least 10 full crop rotations from 1982 to 2019. The experiment included five different pre-crops (green fallow, bare fallow, field bean, oat, and maize) followed by three years of cereal cultivation (winter wheat, winter rye, spring barley) in combination with four levels of mineral fertilization (unfertilized; PK 50 %; PK 100 % + N 50 %; PK 100 % + N 100 %). The field trial was conducted as a full factorial split plot design, with spatially randomized field repetitions in four blocks. It was found that within the ten crop rotations from 1983 to 2019, the mean relative yields of wheat as the first subsequent crop were significantly higher after green fallow (139 %) than grain legume (field bean)/bare fallow (120 %), maize (100 %) and oat (94 %). A rotational system of green fallow not only enhanced the yield effects of the 1st subsequent crop (winter wheat), but also extended the benefits to the 2nd (winter rye) and 3rd (spring barley) subsequent crops. Further on, green fallow had a synergistic effect of PK 100 % + N 100 % on grain yield of winter wheat when compared to bare fallow, field bean, oat and maize. Green fallow and continuous soil cover with crop residue mulch with mineral fertilizer application improved N cycling and crop productivity by increasing soil N availability in the agroecosystem. A short period of bare fallow led to increase net N mineralization of organic matter compared with cropped lands and increases yield in immediately following crop when water availability is sufficient.

1. Introduction

In order to increase the sustainability of agriculture, the policy known as the Common Agricultural Policy (CAP), was legislated in the 1980s in the EU to cut off the grain production of cereal crops (European Union, 1992). Therefore, fallow land was introduced as a tool to reduce agricultural production in Europe. However, the CAP has been reformed today to reduce fallow lands to 5% in a program known as the "Ecological Focus Area" which should ensure greater environmental sustainability (Pe'er et al., 2014; Fraser, 2016; Hertzog et al., 2023).

Integrating fallow land into a rotation system and implementing proper N fertilizer management not only enhances crop diversity and increases yields but also promotes sustainability in agroecosystems (Böldt et al., 2021; De Notaris et al., 2020). In addition to the fact that a short-term fallowing without vegetation allows the land to recover and store organic matter by retaining moisture, it also disturbs the life cycle of pests and soil borne diseases by temporarily removing their hosts. However, annual bare fallow can be susceptible to leaching, disruption of soil structure over time and erosion. Therefore, a partial fallow system with annual legumes used as green manure referred to as "green fallow"

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has been integrated into rotation systems as a soil conserving and more bio-resource efficient alternative to bare fallow. This approach is particularly effective in low-input management systems, where herbicides, pesticides, and mineral fertilizers are not applied, and, as in the case of the current long-term experiment (LTE), no irrigation is utilized. Fallow periods in which pre-crops or cover crops such as legumes (clover mulch used as green fallow) are integrated into the rotation system provide more benefits to the agroecosystem compared to bare fallow. Thus, diversified crop rotations not only increase the crop yield but also improve the nutrient cycling (specifically N), microbial activity and finally the soil fertility (Biederbeck et al., 2005; Gan et al., 2015; Hertzog et al., 2023). Although fallow with cover crops has been shown to provide a number of ecosystem service benefits (Marini et al., 2020), the effects of short fallow periods without vegetation, compared to other leguminous/cereal pre-crops, are not well understood in long-term rotations under changing climate conditions. There is also a knowledge gap on the rotation length where cover crops can provide sustainability by sequestering N in the agroecosystem.

Using legumes (e. g. clover species, field bean or pea) as cover crops in rotation with cereal crops is a very common principle for designing crop rotations (Böldt et al., 2021; De Notaris et al., 2020). The annual legumes used as green fallow in semiarid climates can result in considerable N_2 -fixation without excessive depletion of soil water reserves for the subsequent wheat crops (Biederbeck et al., 2005). However, the duration of the appropriate crop rotation to provide noticeable benefits to the agroecosystem is still a knowledge gap, and more research is needed on when and how long to integrate cover crops into the management practices depending on climate and environmental condition. For example, the use of legumes as a cover crop in a pure monoculture system can increase N leaching in autumn through mineralization of organic matter and high rainfall (Gollner et al., 2020; De Notaris et al., 2020). In contrast, cover crops such as ryegrass, and brassicas can take up the N surplus from the previous cultivation more effectively (Justes, 2017). Several studies have shown that, depending on climate, environmental condition and plant species, non-legume cover crops, can take up the N surplus from arable lands into their above- and below ground biomass ranging from 80 kg N ha⁻¹ with rye, ryegrass, winter barley (in Germany) to 200 kg N ha⁻¹ with oilseed rape (in the USA) and provide the nutrients for the subsequent crops (Komainda et al., 2016; Justes, 2017). The combined application of mineral N and high-quality organic amendments, such as green manures of leguminous crops, can potentially reduce N losses. This occurs through a gradual reduction in N application rates and enhancements in the productivity of agricultural practices (Bowles et al., 2020; Vaziritabar et al., 2024).

Long-term experiments (LTEs) that integrate fallow lands, including green and bare fallow are hardly available in Europe today. Therefore, there is a great need to investigate the effects of rotational cropping systems that include different forms of fallow over a long time. The LTE “Biological Nitrogen Fixation” is one among those experiments that have been managing fallow land (green vs. bare fallow) for more than 40 years in which the long-term effects of different land uses on productivity of subsequent cereal crops under changing climate conditions can be investigated. This LTE is therefore very valuable and well suited for evaluating the effects of fallowing of arable land in comparison with grain legume and non-legume crops on the yields of subsequent cereal crops or the entire crop rotation. In this context we evaluate the following hypotheses: (i) Green fallow (clover mulch) and grain legume (field bean) increase grain yields in the immediate subsequent wheat crop (H1). (ii) Positive pre-crop effects are also expected in the second and third subsequent crops throughout ten rotations (H2). (iii) Green fallow and field bean have synergistic effect on NPK fertilization in the subsequent cereal crops (H3). (vi) Bare fallow is inferior to the legume pre-crops (green fallow and field bean) and has a similar pre-crop effect to the cereal crops (maize and oats) (H4).

2. Material and methods

2.1. Site characteristics and soil conditions

Data from an ongoing LTE were compiled for the period from 1982 until 2021 at the research station “Weilburger Grenze” Giessen (50° 36' 12" N, 8° 39' 16" E, 158 m a. s. l.) at the Justus Liebig University Giessen (Germany). The climate of the site is characterized by an average annual air temperature of 9.9 °C and annual precipitation sum of 668 mm (average from 1982 to 2021) (Tables S1 and S2). To assess the influence of climatic conditions on pre-crops effects in cereal grain yields, the annual average of air temperature and sum of precipitation were evaluated for the period from 1983 to 2021. Air temperature was categorized into three levels of cold (≤ 5), mild (6–20) and hot (> 20 °C). Precipitation was classified into three levels of dry (below the 25th percentile), normal (between the 25th and 75th percentiles) and wet (above the 75th percentile), based on the total annual precipitation sum. The annual average of air temperature during growing season (from March to July) ranged from 10.5 to 14.5 °C, while the total precipitation sum ranged from 110 to 410 mm within the period of 1983–2021. The soil is classified as Fluvic Gleyic Cambisol (IUSS Working Group WRB 2015) characterized by a silty clay texture (0–30 cm) with a clay content of approximately 39–49 %, silt content of 40–58 %, soil organic carbon (SOC) content of 1.6 %, plant available phosphorus ranging from 110 to 200 mg P kg⁻¹, and plant available potassium ranging between 40 and 400 mg K kg⁻¹ soil (0–30 cm). The usable field capacity (0–100 cm) was 123 mm, with a bulk density of 1.2–1.3 g cm⁻³, and a soil pH value of 6–6.4.

2.2. Experimental design and treatments

The field experiment included two main factors (A) pre-crops (PC) with 5 levels of maize, oat, field bean, green fallow, and bare fallow and (B) mineral NPK fertilization with 4 levels (unfertilized/control; PK 50 %; PK 100 % + N 50 %; PK 100 % + N 100 %) applied to subsequent cereal species (winter wheat, winter rye and spring barley). The field trial (with an individual plot size of 42 m²) conducted as a fully factorial split plot design, with spatially randomized field repetitions in four blocks resulting in a total of 80 plots (Figure S1). The four-year rotational crop sequence (1–4) was as follows: 1) In the first year the entire trial area was only cultivated with five different pre-crops (main factor A) arranged parallel to each other in a separate plot, including Corn-Cob-Mix (CCM) maize (*Zea mays* cvs. Lorado, Sunshinos), summer oat (*Avena sativa* cvs. Flocke, Expanter, Fleuron), field bean (*Vicia faba* cvs. Kristall, Alfred, Sirocco, Hiverna), crimson clover (green fallow) / hairy vetch (*Trifolium incarnatum* cv. Kardinal / *Vicia villosa* cv. candy) used as green mulch, and bare fallow (BonaRes Repository). These five pre-crops had a main crop status within the rotational system. 2) In the second year, winter wheat was grown as the first successive main crop after five different pre-crops on the entire experimental area, followed by 3) winter rye as the second successive main crop in the third year and by 4) spring barley in the fourth year (Table S3). The crops of the 1st-4th rotational systems were not simultaneously grown in every year, instead they cycled every fourth year according to the four-year rotational sequence. Therefore, the same pattern of pre-crop treatments took place in the rotation for the last ten times in 1982, 1986, 1990, 1994, 1998, 2002, 2006, 2010, 2014 and 2018 (Table S3). In the first year of the rotation, the entire biomass of crimson clover as green mulch was ploughed into the soil, whereas field bean, oat and maize were harvested and after harvest the standing residues were incorporated into the soil (in 25 cm depth) approximately three weeks after harvesting the last pre-crop. The straw residues from the following year's winter wheat, winter rye and spring barley were incorporated into the soil (in 25 cm depth) approximately three weeks after harvest of each crop.

In each rotational year's mineral N (as calcium ammonium nitrate) was fertilized to non-legume pre-crops as follows: oats were uniformly

fertilized with 135 (divided into 80 kg N ha⁻¹ at growing stage of DC 28 plus 55 kg N ha⁻¹ at growing stage of DC 31) and maize with 130 kg N ha⁻¹ at germination stage to ensure that they provided sufficient biomass for the following crops. Mineral NPK fertilization (main factor B) to subsequent cereal species (winter wheat, winter rye and spring barley) included four sub-treatments: (1) unfertilized/control, (2) only PK 50 % + 0 % N dosage, (3) PK 100 % + 50 % N reduced dosage (90, 60 and 60 kg N ha⁻¹ for wheat, rye and barley respectively) and (4) PK 100 % + 100 % N full dosage (180, 120 and 90 kg N ha⁻¹ for wheat, rye and barley, respectively). Calcium ammonium nitrate was used for nitrogen fertilization. For both 50 % and 100 % N dosages, the total amount of N was divided in three split dosage as 40/30/20 kg N ha⁻¹ at the growth stage of DC 25/29/51 or 80/60/40 kg N ha⁻¹ at growing stage of DC 25/29/51 in winter wheat (2nd year of rotation); two split dosage as 30/30 kg N ha⁻¹, at the growth stage of DC 26/33 or 60/60 kg N ha⁻¹ at growing stage of DC 26/33 in winter rye (3rd year of rotation); and 60 kg N ha⁻¹ at the growth stage of DC 31 or 90 kg N ha⁻¹ at growth stage of DC 31 in spring barley (4th year of rotation). Phosphorus was applied as triple superphosphate (200 g P kg⁻¹) at two levels of 20 kg P ha⁻¹ (reduced dosage) and 39 kg P ha⁻¹ (full dosage), whereas potassium was fertilized as Korn-Kali® (332 g K kg⁻¹) at two levels of 50 kg K ha⁻¹ (reduced dosage) and 100 kg K ha⁻¹ (full dosage). Both fertilizers were applied at the beginning of germination in spring (middle of April) at the growth stage of DC 25 for winter wheat, winter rye and spring barley.

The grains of each plot were harvested within a day using a plot combine harvester (Wintersteiger, Austria). The dry matter of grain samples was determined at 100 % dry matter (DM) after drying at 105 °C in a drying cabinet (WTB Binder ED 53) for three days. The quality of crop residues incorporated into the soil was determined by the amount of aboveground N inputs provided by PCs (maize, oat, field bean, green fallow, bare fallow) to the following cropping season (by using a UNICUBE CHNS Analyzer, Germany) in 2018. On average, crimson clover as a green mulch provided the highest levels of N input of 116.4 kg N/ha for the following cropping seasons. In contrast, field bean provided only 21.7 kg N/ha, oat 25.4 kg N/ha and maize 35.3 kg N/ha. At the same time, the highest soil mineral N (N_{min}) was found for clover (103 kg ha⁻¹) and lower values for field bean (57 kg ha⁻¹), oat (40 kg ha⁻¹), maize (53 kg ha⁻¹) and bare fallow (72 kg ha⁻¹) after the incorporation of crop residues into the soil. In addition, the quantity of crop residues incorporated into the soil determined in terms of aboveground C inputs provided by PCs (clover 6.4, field bean 1.2, oat 6.2, maize 7.8 t DM ha⁻¹) to the following cropping season (Vaziritabar et al., 2024). To prepare for the soil analysis, soil samples (100 g) were collected from the topsoil (0–30 cm), dried at 40 °C for three days, sieved (2 mm) and grinded afterwards (with Retsch mixer mill MM 400, Germany). Soil organic carbon (SOC) and total nitrogen (Nt) content were determined in the years of the 9th and 10th crop rotations using the combustion method with a UNICUBE CHNS Analyzer, Germany.

2.3. Statistical analysis

The statistical evaluation of grain yields per crop rotation and per year was carried out over a total of 10 rotations in the period from 1983–2021 according to treatment factors (A: pre-crops and B: mineral NPK fertilization) on biomass yield (H1) and (H2). For this purpose, a multi-factor analysis of variance (two-way ANOVA model) with fixed factors: pre-crops and mineral NPK fertilization as well as subsequent cereal crops (winter wheat, winter rye, and spring barley) and random factors: year and replication was applied based on GLM (Generalized Linear Model) procedure (H3) to examine the difference of diverse categorically independent variables on a dependent variable. In addition, the interaction (H4) between both test factors (pre-crops and mineral NPK fertilization) was examined. Furthermore, the respond of subsequent cereal crops to fixed factors (pre-crops and mineral NPK fertilization) have been investigated over the years and tested for

significant interactions. Differences between groups were investigated based on model coefficients and using the Tukey's post-hoc analysis. Mean comparisons were performed for each variable with a probability of $p < 0.05$. The statistical calculations were carried out on the basis of SAS version 9.4 (Littell et al., 2006). In order to take into account the role of climatic conditions (focus on precipitation and air temperature) in the evaluation of the effects of the previous crop, a principal component analysis (PCA) with biplot was carried out using the FactoMineR and factoextra packages in R version 4.4.2.

3. Results

3.1. Effect of green fallow and grain legumes (field bean) on subsequent crops

Within the ten crop rotations from 1983 to 2019 the integration of different pre-crops had a significant ($p < 0.001$) effect on grain yield of winter wheat as the first subsequent crop (Table S4). The ranking of the mean relative yields of wheat was as follows: green fallow 139 % > field bean/bare fallow 120 % > maize 100 % > oat 94 %. Winter wheat after green fallow (clover mulch) achieved the highest grain yields on a long-term average and was superior to all other pre-crop combinations, although the difference to field bean/bare fallow was not statistically significant (Fig. 1). Within the ten crop rotations, winter wheat after field bean and bare fallow had the same yield effects, except in the first year (1983). On the other hand, the cereal pre-crops (oat and maize) were clearly inferior to green fallow, bare fallow and field bean (Fig. 1).

3.2. Effect of bare fallow on subsequent crops

Within the ten crop rotations, bare fallow was always inferior to green fallow in its effect on the subsequent wheat, except in 1983 and 2011 when there were no significant differences between these two pre-crops (Fig. 1). Comparing bare fallow with field bean it is noticeable that the yield effect on subsequent wheat was statistically identical for both preceding crops in eight out of ten years. There was a different reaction in only two years. Firstly, in 2003 when the effect of bare fallow was lower than that of field bean and in 2011 when bare fallow had a higher yield effect than field bean (Fig. 1). The effects on the second subsequent crop (winter rye) showed that bare fallow is significantly inferior to green fallow in nine out of ten years. In contrast, there were only minor differences with the other pre-crops. For example, the effect of bare fallow on rye was partly identical to that of field bean (1984, 1992, 2000, 2012), oats (1992, 2000, 2012) and maize (1996, 2000, 2004, 2008, 2012) (Fig. 1). In the third subsequent crop, bare fallow was inferior to green fallow in eight out of ten years and in two years (2009 and 2017) significantly yielded less than all comparative pre-crops. Compared to field bean, bare fallow was inferior in four years (1997, 2005, 2009, 2017) and equal in other years (1989, 1993, 2001, 2013). In most years, however (seven out of ten trial years), the bare fallow effect was identical to that of oats and maize.

3.3. Pre-crop effects in the second and third subsequent crops throughout ten rotations

Within the entire period of the ten crop rotations the integration of different pre-crops also had a significant ($p < 0.001$) effect on grain yield of winter rye as the second subsequent crop (Table S4). The ranking of the mean relative grain yields was as follows: green fallow 111 % > field bean/maize 100 %, oats 99 % > bare fallow 93 % (Fig. 1). However, the pre-crops effect on rye grain yields was lower than those effects on winter wheat (1st subsequent crop) and varied over the entire period. It can be observed that green fallow was significantly superior to all other pre-crops in 1988, 1992, 1996, 2004, 2012 and 2016. In other years, however, such as 1984, 2000, 2008 and 2020, green fallow had the same yield effect as field bean, oats and maize.

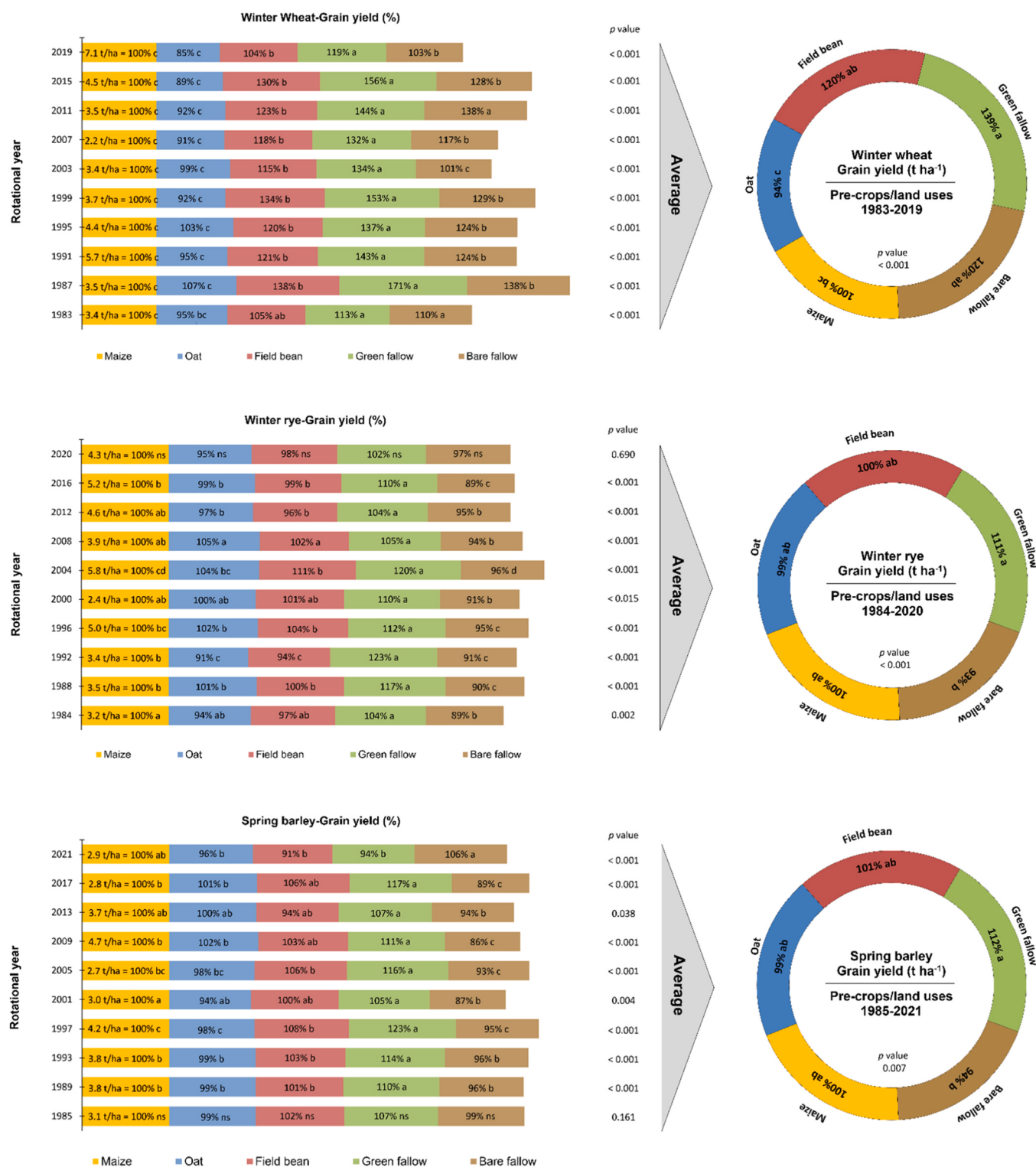


Fig. 1. Cumulative percentage of cereal yields (in percent, maize = 100 %) derived from pre-crops on subsequent winter wheat (1st subsequent crop), winter rye (2nd subsequent crop) and spring barley (3rd subsequent crop) within the crop rotation (1) pre-crops – (2) winter wheat – (3) winter rye – (4) spring barley, LTE Giessen 1983–2021. (Main effects of factor A, different letters indicate significant differences between means, ns: not significant).

Furthermore, the effect of bare fallow on winter rye has worsened in comparison with the first subsequent crop (winter wheat). This can be seen from the fact that the rye yields after bare fallow were the lowest in seven out of 10 years (1984, 1988, 1996, 2000, 2004, 2008, 2016), whereby the yield differences were only statistically significant in 1988 and 2016. In other years, bare fallow yields were statistically equal to field bean (1984, 1992, 2000, 2012), oats (1992, 2000, 2012) or maize

(1996, 2000, 2004, 2008, 2012). When evaluating crop rotation, it is also important to observe the lasting effects of pre-crops in spring barley as a 3rd subsequent crop within the 4th and last year of rotational cycle. It was found that spring barley followed green fallow had a higher grain yield and was ahead of other pre-crops like field bean, oat, maize, and bare fallow (Fig. 1).

Table 1

Interaction effects (A x B) between pre-crops (A) and mineral NPK fertilization (B) on grain yields (t ha^{-1}) of winter wheat (as 1st subsequent crop), LTE Giessen 1983–2019 (FB: field bean, GF: green fallow, BF: bare fallow). Different compact letters indicate significant differences between pre-crops or the four fertilizer treatments ($p < 0.01$).

Mineral NPK fertilization (Factor B)	Pre-crops (factor A)					Mean
	Maize	Oat	FB	GF	BF	
Crop rotation no. 1 (1983–1985, winter wheat 1983)						
Unfertilized/control	2.36 gh	1.97 h	2.63 fg	3.38 e	2.80 f	2.62c
+PK 50 %	2.29 gh	1.97 h	2.81 f	3.63 de	2.97 f	2.73c
+PK 100 % +N 50 %	3.84 d	3.83 d	3.93 cd	4.01 cd	4.32 bc	3.98 b
+PK 100 % +N 100 %	5.27 a	5.33 a	5.14 a	4.54 b	5.09 a	5.07 a
Mean	3.44 cd	3.27 d	3.63 bc	3.89 a	3.79 ab	
p value (A): < 0.001	p value (B): < 0.001			p value (A x B): < 0.001		
Crop rotation no. 2 (1987–1989, winter wheat 1987)						
Unfertilized/control	1.86 ij	2.36 i	3.68 h	5.19 e	3.85 h	3.39c
+PK 50 %	1.81 j	2.19 ij	3.88 h	5.46 de	4.13 gh	3.49c
+PK 100 % +N 50 %	4.59 fg	4.66 f	5.93 bcd	6.39 b	5.72 cd	5.46 b
+PK 100 % +N 100 %	5.87 cd	5.91 bcd	5.96 bc	7.11 a	5.83 cd	6.14 a
Mean	3.53c	3.78c	4.86 b	6.04 a	4.88 b	
p value (A): < 0.001	p value (B): < 0.001			p value (A x B): < 0.001		
Crop rotation no. 3 (1991–1993, winter wheat 1991)						
Unfertilized/control	3.21 i	3.51 i	5.44 gh	7.43 e	5.70 g	5.06c
+PK 50 %	3.23 i	3.38 i	5.51 gh	7.59 e	5.08 h	4.96c
+PK 100 % +N 50 %	7.69 de	6.61 f	7.93 cde	8.45 abc	8.56 ab	7.85 b
+PK 100 % +N 100 %	8.66 ab	8.24 bcd	8.76 ab	9.03 a	8.87 a	8.71 a
Mean	5.70c	5.43c	6.91 b	8.13 a	7.05 b	
p value (A): < 0.001	p value (B): < 0.001			p value (A x B): < 0.001		
Crop rotation no. 4 (1995–1997, winter wheat 1995)						
Unfertilized/control	2.55 h	2.62 h	3.81 g	4.90 f	4.06 g	3.59c
+PK 50 %	2.49 h	2.64 h	3.85 g	5.12 f	4.10 g	3.64c
+PK 100 % +N 50 %	5.56 e	5.68 e	6.30 d	6.89 bc	6.56 cd	6.20 b
+PK 100 % +N 100 %	7.12 ab	7.33 a	7.25 ab	7.32 a	7.23 ab	7.25 a
Mean	4.43c	4.57c	5.30 b	6.06 a	5.49 b	
p value (A): 0.001	p value (B): < 0.001			p value (A x B): < 0.001		
Crop rotation no. 5 (1999–2001, winter wheat 1999)						
Unfertilized/control	2.18 h	1.90 h	3.89 efg	4.75 cde	3.59 fg	3.26c
+PK 50 %	2.14 h	1.89 h	4.00 efg	4.82 cde	3.34 g	3.24c
+PK 100 % +N 50 %	4.47 def	4.01 efg	5.45 bcd	6.37 ab	5.65 abc	5.19 b
+PK 100 % +N 100 %	5.87 ab	5.66 abc	6.31 ab	6.53 a	6.29 ab	6.13 a
Mean	3.66c	3.36c	4.91 b	5.62 a	4.72 b	
p value (A): 0.001	p value (B): < 0.001			p value (A x B): < 0.001		
Crop rotation no. 6 (2003–2005, winter wheat 2003)						
Unfertilized/control	1.84 i	2.13 ghi	2.87 f	3.71 e	2.25 g	2.56c
+PK 50 %	1.94 hi	2.21 gh	2.95 f	4.14 d	2.11 ghi	2.67c
+PK 100 % +N 50 %	4.77 bc	4.14 d	4.68c	4.98 abc	4.30 d	4.57 b
+PK 100 % +N 100 %	4.93 abc	4.85 bc	5.06 ab	5.22 a	4.90 bc	4.99 a
Mean	3.37c	3.33c	3.89 b	4.51 a	3.39c	
p value (A): 0.001	p value (B): < 0.001			p value (A x B): < 0.001		
Crop rotation no. 7 (2007–2009, winter wheat 2007)						
Unfertilized/control	1.37 g	1.37 g	1.91 f	2.12 f	1.85 f	1.72c
+PK 50 %	1.30 g	1.37 g	1.99 f	2.59 de	1.85 f	1.82c
+PK 100 % +N 50 %	2.87 cd	2.43 e	3.19 ab	3.47 a	3.14 bc	3.02 b
+PK 100 % +N 100 %	3.27 ab	2.89 cd	3.27 ab	3.45 a	3.46 a	3.27 a
Mean	2.20c	2.01c	2.59 b	2.91 a	2.58 b	
p value (A): < 0.001	p value (B): < 0.001			p value (A x B): 0.004		
Crop rotation no. 8 (2011–2013, winter wheat 2011)						
Unfertilized/control	2.29	2.19	3.09	4.22	4.05	3.17c
+PK 50 %	2.46	2.11	3.23	4.61	3.77	3.24c
+PK 100 % +N 50 %	4.29	4.04	5.11	5.36	5.54	4.87 b
+PK 100 % +N 100 %	4.80	4.41	5.60	5.79	5.74	5.27 a
Mean	3.46c	3.19c	4.26 b	5.00 a	4.77 a	
p value (A): < 0.001	p value (B): < 0.001			p value (A x B): 0.052		
Crop rotation no. 9 (2015–2017, winter wheat 2015)						
Unfertilized/control	3.21 jk	2.20 l	4.30 hi	5.66 fg	3.63 ij	3.80c
+PK 50 %	2.40 kl	2.14 i	4.40 hi	6.15 ef	4.32 hi	3.88c
+PK 100 % +N 50 %	5.17 gh	4.82 gh	6.53 def	7.62 bc	6.69 de	6.17 b
+PK 100 % +N 100 %	7.19 cd	6.82 cde	8.09 ab	8.63 a	8.35 ab	7.82 a
Mean	4.49c	3.99c	5.83 b	7.02 a	5.75 b	
p value (A): < 0.001	p value (B): < 0.001			p value (A x B): 0.031		
Crop rotation no. 10 (2016–2019, winter wheat 2016)						
Unfertilized/control	5.18	4.03	5.37	6.97	5.25	5.36c
+PK 50 %	5.26	3.48	5.34	7.42	4.39	5.29c
+PK 100 % +N 50 %	8.11	7.30	8.88	9.32	9.07	8.54 b
+PK 100 % +N 100 %	9.83	9.36	9.97	10.20	10.09	9.89 a
Mean	7.09 b	6.04c	7.39 b	8.48 a	7.34 b	
p value (A): < 0.001	p value (B): < 0.001			p value (A x B): 0.070		

Table 2

Interaction effects (A x B) between pre-crops (A) and mineral NPK fertilization on grain yields (t ha^{-1}) of winter rye (as 2nd subsequent crop), LTE Giessen 1984–2020. (FB: field bean, GF: green fallow, BF: bare fallow, different letters indicate significant differences between means).

Mineral NPK fertilization (Factor B)	Pre-crops (factor A)					Mean
	Maize	Oat	FB	GF	BF	
Crop rotation no. 1 (1983–1985, winter rye 1984)						
Unfertilized/control	2.13	1.88	1.79	2.17	1.60	1.91c
+PK 50 %	1.97	2.01	1.73	1.98	1.56	1.85c
+PK 100 % +N 50 %	4.07	3.78	4.16	4.34	3.72	4.01 b
+PK 100 % +N 100 %	4.80	4.53	4.88	5.06	4.70	4.79 a
Mean	3.24 a	3.05 ab	3.14 ab	3.39 a	2.89 b	
p value (A): 0.002	p value (B): < 0.001		p value (A x B): 0.726			
Crop rotation no. 2 (1987–1989, winter rye 1988)						
Unfertilized/control	2.29	2.32	2.19	2.93	1.91	2.33c
+PK 50 %	2.27	2.42	2.21	3.08	1.70	2.33c
+PK 100 % +N 50 %	4.44	4.46	4.50	4.95	4.26	4.52 b
+PK 100 % +N 100 %	5.10	5.03	5.18	5.51	4.82	5.13 a
Mean	3.52 b	3.56 b	3.52 b	4.12 a	3.17c	
p value (A): < 0.001	p value (B): < 0.001		p value (A x B): 0.398			
Crop rotation no. 3 (1991–1993, winter rye 1992)						
Unfertilized/control	1.86 g	1.92 g	1.94 g	2.93 f	1.85 g	2.10c
+PK 50 %	1.94 g	1.85 g	1.81 gh	3.10 f	1.54 h	2.05c
+PK 100 % +N 50 %	4.23 d	3.67 e	3.89 e	4.86c	3.73 e	4.07 b
+PK 100 % +N 100 %	5.55 a	4.92c	5.06 bc	5.78 a	5.23 b	5.31 a
Mean	3.40 b	3.09c	3.18c	4.17 a	3.09c	
p value (A): < 0.001	p value (B): < 0.001		p value (A x B): < 0.001			
Crop rotation no. 4 (1995–1997, winter rye 1996)						
Unfertilized/control	3.36 d	3.58 d	3.61 d	4.43c	2.76 e	3.55c
+PK 50 %	3.37 d	3.37 d	3.65 d	4.55c	2.70 e	3.53c
+PK 100 % +N 50 %	6.16 b	6.23 b	6.24 b	6.23 b	6.15 b	6.20 b
+PK 100 % +N 100 %	7.04 a	7.16 a	7.23 a	7.16 a	7.37 a	7.19 a
Mean	4.98 bc	5.08 b	5.18 b	5.59 a	4.74c	
p value (A): < 0.001	p value (B): < 0.001		p value (A x B): < 0.001			
Crop rotation no. 5 (1999–2001, winter rye 2000)						
Unfertilized/control	1.31	1.43	1.46	1.91	1.06	1.43c
+PK 50 %	1.34	1.48	1.50	1.73	1.04	1.42c
+PK 100 % +N 50 %	3.22	3.11	3.52	3.44	3.02	3.26 b
+PK 100 % +N 100 %	3.90	3.74	3.44	3.65	3.78	3.70 a
Mean	2.44 ab	2.44 ab	2.48 ab	2.68 a	2.22 b	
p value (A): < 0.001	p value (B): < 0.001		p value (A x B): 0.217			
Crop rotation no. 6 (2003–2005, winter rye 2004)						
Unfertilized/control	3.16 e	3.38 e	4.14 de	4.99 d	3.15 e	3.76c
+PK 50 %	3.33 e	3.49 e	4.13 de	5.07 d	3.14 e	3.83c
+PK 100 % +N 50 %	6.95c	7.65c	7.62c	7.50c	6.87c	7.32 b
+PK 100 % +N 100 %	9.61 ab	9.56 ab	9.64 ab	10.02 a	8.92 b	9.55 a
Mean	5.76 cd	6.02 bc	6.38 b	6.89 a	5.52 d	
p value (A): < 0.001	p value (B): < 0.001		p value (A x B): 0.001			
Crop rotation no. 7 (2007–2009, winter rye 2008)						
Unfertilized/control	2.35	2.65	2.53	2.68	2.24	2.49c
+PK 50 %	2.60	2.54	2.62	2.89	2.18	2.57c
+PK 100 % +N 50 %	4.99	5.23	4.91	5.16	4.67	4.99 b
+PK 100 % +N 100 %	5.65	5.89	5.82	5.63	5.58	5.71 a
Mean	3.90 ab	4.08 a	3.97 a	4.09 a	3.67 b	
p value (A): 0.001	p value (B): < 0.001		p value (A x B): 0.302			
Crop rotation no. 8 (2011–2013, winter rye 2012)						
Unfertilized/control	3.13 ef	3.05 efg	2.95 efg	3.58 d	3.00 efg	3.14c
+PK 50 %	3.16 e	2.75 fg	2.74 fg	3.63 d	2.65 g	2.98c
+PK 100 % +N 50 %	5.62c	5.66c	5.44c	5.67c	5.62c	5.60 b
+PK 100 % +N 100 %	6.71 ab	6.56 ab	6.80 a	6.46 ab	6.36 b	6.58 a
Mean	4.65 ab	4.50 b	4.48 b	4.83 a	4.41 b	
p value (A): 0.001	p value (B): < 0.001		p value (A x B): 0.013			
Crop rotation no. 9 (2015–2017, winter rye 2016)						
Unfertilized/control	3.13	3.13	3.27	3.71	2.54	3.16c
+PK 50 %	4.07	3.25	3.17	3.84	3.31	3.53c
+PK 100 % +N 50 %	6.04	6.37	6.28	6.91	5.33	6.19 b
+PK 100 % +N 100 %	7.74	8.08	8.04	8.63	7.58	8.01 a
Mean	5.25 b	5.21 b	5.19 b	5.77 a	4.69c	
p value (A): 0.001	p value (B): < 0.001		p value (A x B): 0.164			
Crop rotation no. 10 (2016–2019, winter rye 2017)						
Unfertilized/control	2.87	2.78	2.45	2.76	2.43	2.66c
+PK 50 %	2.51	2.31	2.18	2.63	2.41	2.41c
+PK 100 % +N 50 %	5.19	4.99	5.37	5.27	5.18	5.20 b
+PK 100 % +N 100 %	6.71	6.26	6.92	6.91	6.73	6.71 a
Mean	4.32 a	4.08 a	4.23 a	4.39 a	4.19 a	
p value (A): 0.690	p value (B): < 0.001		p value (A x B): 0.973			

Table 3

Interaction effects (A x B) between pre-crops (A) and mineral NPK fertilization on grain yields (t ha^{-1}) of spring barley (as 3rd subsequent crop), LTE Giessen 1985–2021 (FB: field bean, GF: green fallow, BF: bare fallow, different letters indicate significant differences between means).

Mineral NPK fertilization (Factor B)	Pre-crops (factor A)					Mean
	Maize	Oat	FB	GF	BF	
Crop rotation no. 1 (1983–1985, spring barley 1985)						
Unfertilized/control	2.18	2.37	2.45	2.59	2.10	2.34c
+PK 50 %	2.58	2.36	2.50	2.79	2.13	2.47c
+PK 100 % +N 50 %	3.46	3.35	3.48	3.59	3.69	3.51 b
+PK 100 % +N 100 %	4.16	4.14	4.22	4.24	4.33	4.22 a
Mean	3.09 a	3.06 a	3.16 a	3.30 a	3.06 a	
p value (A): 0.161	p value (B): < 0.001		p value (A x B): 0.381			
Crop rotation no. 2 (1987–1989, spring barley 1989)						
Unfertilized/control	2.91 ef	2.92 def	2.91 ef	3.59c	2.83 ef	3.03c
+PK 50 %	3.05 de	3.02 def	3.22 d	3.64c	2.73 f	3.13c
+PK 100 % +N 50 %	4.29 b	4.26 b	4.36 b	4.46 b	4.17 b	4.31 b
+PK 100 % +N 100 %	4.97 a	4.81 a	4.86 a	5.03 a	4.89 a	4.91 a
Mean	3.80 b	3.75 b	3.84 b	4.18 a	3.66 b	
p value (A): < 0.001	p value (B): < 0.001		p value (A x B): 0.046			
Crop rotation no. 3 (1991–1993, spring barley 1993)						
Unfertilized/control	3.13	3.25	3.44	3.95	3.32	3.42c
+PK 50 %	3.27	3.43	3.83	4.03	3.31	3.57c
+PK 100 % +N 50 %	4.15	4.03	4.03	4.44	3.77	4.08 b
+PK 100 % +N 100 %	4.72	4.43	4.42	4.92	4.33	4.56 a
Mean	3.82 b	3.79 b	3.93 b	4.34 a	3.68 b	
p value (A): < 0.001	p value (B): < 0.001		p value (A x B): 0.402			
Crop rotation no. 4 (1995–1997, spring barley 1997)						
Unfertilized/control	2.93	2.91	3.38	3.93	2.73	3.17c
+PK 50 %	3.00	3.05	3.46	4.50	2.88	3.38c
+PK 100 % +N 50 %	5.15	4.83	5.30	6.09	4.75	5.22 b
+PK 100 % +N 100 %	5.83	5.79	6.07	6.24	5.75	5.93 a
Mean	4.23c	4.15c	4.55 b	5.19 a	4.03c	
p value (A): < 0.001	p value (B): < 0.001		p value (A x B): 0.090			
Crop rotation no. 5 (1999–2001, spring barley 2001)						
Unfertilized/control	1.97	1.99	2.19	2.50	1.62	2.05c
+PK 50 %	2.37	2.25	2.34	2.33	1.83	2.22c
+PK 100 % +N 50 %	3.33	3.09	3.36	3.73	3.10	3.32 b
+PK 100 % +N 100 %	4.45	4.02	4.21	4.13	3.94	4.15 a
Mean	3.03 a	2.84 ab	3.02 ab	3.17 a	2.62 b	
p value (A): 0.004	p value (B): < 0.001		p value (A x B): 0.787			
Crop rotation no. 6 (2003–2005, spring barley 2005)						
Unfertilized/control	1.42	1.49	1.75	2.04	1.38	1.61c
+PK 50 %	1.62	1.69	1.88	2.26	1.49	1.79c
+PK 100 % +N 50 %	3.60	3.55	3.68	3.86	3.22	3.58 b
+PK 100 % +N 100 %	4.26	3.99	4.27	4.50	4.00	4.20 a
Mean	2.72 bc	2.68 bc	2.90 b	3.16 a	2.52c	
p value (A): < 0.001	p value (B): < 0.001		p value (A x B): 0.848			
Crop rotation no. 7 (2007–2009, spring barley 2009)						
Unfertilized/control	4.32	4.83	4.66	4.97	3.61	4.48 d
+PK 50 %	4.72	4.61	4.91	5.10	4.21	4.71c
+PK 100 % +N 50 %	4.79	4.91	4.86	5.45	3.86	4.78 b
+PK 100 % +N 100 %	4.96	4.81	4.87	5.31	4.51	4.89 a
Mean	4.70 b	4.79 b	4.82 ab	5.21 a	4.05c	
p value (A): < 0.001	p value (B): 0.011		p value (A x B): 0.437			
Crop rotation no. 8 (2011–2013, spring barley 2013)						
Unfertilized/control	1.86	1.65	1.50	1.92	1.36	1.66 b
+PK 50 %	1.79	1.73	1.71	2.44	1.51	1.84 b
+PK 100 % +N 50 %	5.18	5.58	5.01	5.70	5.71	5.44 a
+PK 100 % +N 100 %	6.05	5.88	5.76	5.86	5.39	5.79 a
Mean	3.72 ab	3.71 ab	3.50 ab	3.98 a	3.49 b	
p value (A): 0.039	p value (B): < 0.001		p value (A x B): 0.437			
Crop rotation no. 9 (2015–2017, spring barley 2017)						
Unfertilized/control	1.96	1.98	2.33	2.75	1.75	2.15c
+PK 50 %	1.98	2.20	2.36	2.96	1.85	2.27c
+PK 100 % +N 50 %	3.26	3.21	3.51	3.54	2.92	3.29 b
+PK 100 % +N 100 %	4.17	4.08	3.88	4.08	3.58	3.95 a
Mean	2.84 b	2.87 b	3.02 ab	3.33 a	2.52c	
p value (A): < 0.001	p value (B): < 0.001		p value (A x B): 0.153			
Crop rotation no. 10 (2016–2019, spring barley 2019)						
Unfertilized/control	1.37	1.32	1.06	1.16	1.70	1.32 d
+PK 50 %	1.80	1.58	1.34	1.45	2.08	1.65c
+PK 100 % +N 50 %	3.94	3.82	3.74	3.84	4.05	3.88 b
+PK 100 % +N 100 %	4.57	4.47	4.49	4.52	4.52	4.51 a
Mean	2.92 ab	2.80 b	2.66 b	2.74 b	3.09 a	
p value (A): < 0.001	p value (B): < 0.001		p value (A x B): 0.623			

3.4. Synergistic effect of pre-crops on NPK fertilization in the subsequent cereal crops

As expected, the combined supply with mineral PK and mineral N (at reduced as well as full dosages) had a positive effect on grain yield of winter wheat, winter rye and spring barley within the entire experimental period (Table S4). At the beginning of the LTE in 1983, the grain yield of winter wheat followed green fallow and full dosage of NPK (100 % N + PK 100 %) was not superior to oat, maize, field bean as a grain legume, and bare fallow (Table 1). Within the 2nd crop rotation in 1987, green fallow and full dosage of NPK had a synergistic effect on grain yield of winter wheat than bare fallow, field bean, oat and maize. Within the 3rd crop rotation in 1991, a lower grain yield was observed in winter wheat followed oat and full dosage of NPK than that of green fallow and bare fallow, respectively. Within the 4th and 5th crop rotation in 1995 and 1999, the same yield effects were observed among pre-crops when the full dosage of NPK was applied. However, in unfertilized plots green fallow had superiority to bare fallow and field bean and was ahead of cereal pre-crops (Table 1). Within the 6th crop rotation in 2003, winter wheat following bare fallow and oat had significantly lower grain yield than green fallow and field bean, when full dosage of NPK were applied. Within the 7th and 9th crop rotation in 2007 and 2015, winter wheat following oat in combination with full dosage of NPK had a lower grain yield compared to green fallow, field bean and bare fallow (Table 1).

In the case of winter rye, within the 3rd crop rotation in 1992, no interactions were observed between green fallow and maize when the full dosage of NPK was applied (Table 2). Furthermore, the grain yield of winter rye following bare fallow, field bean and oat were significantly lower under this condition. The pre-crop effect of green fallow was modified by reduced N (50 % N + 100 % PK) compared to maize and was ahead of field bean, bare fallow and oat (Table 2). Within the 4th crop rotation in 1996, the pre-crops effect was not modified by mineral NPK (Table 2). Within the 6th and 8th crop rotation in 2004 and 2012, the full dosage of NPK modified the pre-crops effect on yield performance of winter rye. So that bare fallow had significantly lower grain yield compared to green fallow, field bean and cereal crops. In terms of spring barley, except the 2nd crop rotation, no interaction effects were observed between pre-crops and mineral NPK through the ten crop rotations (Table S4). Within the 2nd crop rotation, there were no interaction effects between green fallow as well as bare fallow, field bean, oat, and maize at both levels of NPK. Interestingly, in unfertilized plots, spring barley followed green fallow had significantly higher grain yield compared to bare fallow and was ahead of maize, field bean, and oat (Table 3).

3.5. Nt and SOC content of the topsoil depending on pre-crops and NPK fertilization

The soil analysis carried out in the years 2019–2021 (9th and 10th crop rotation) showed a significant ($p < 0.001$) increase of Nt in the topsoil (0–30 cm) compared to bare fallow. Among pre-crops green fallow (clover mulch) increased the Nt of the soil to the highest level of 2.1 g kg^{-1} (Fig. 2). After green fallow, field bean (2.0 g kg^{-1}), oat (1.9 g kg^{-1}) and maize (1.9 g kg^{-1}) caused an increase in the topsoil Nt at the same level. In addition, mineral N fertilizer at both levels (PK 100 % + N 50 % and PK 100 % + N 100 %) significantly ($p < 0.001$) increased the Nt content of the soil to the levels of 2.1 g kg^{-1} compared to the control (2.0 g kg^{-1}) and PK 50 % (1.7 g kg^{-1}) respectively (Fig. 2). Regarding the SOC in the topsoil, green fallow (20.6 g kg^{-1}) and field bean (20.3 g kg^{-1}) were at the same level and significantly ($p = 0.044$) contributed to the increase in SOC compared with oat (19.8 g kg^{-1}), maize and bare fallow (19.6 g kg^{-1}), respectively (Fig. 3). In addition, the SOC was significantly lower at PK 50 % (17.7 g kg^{-1}) than at PK 100 % + N 50 % (21.1 g kg^{-1}), PK 100 % + N 100 % (20.9 g kg^{-1}) and the control (20.1 g kg^{-1}).

3.6. Interactions between pre-crops and climatic conditions

The annual average of air temperature (during the growing season from March to July) in the entire ten-year crop rotation (1983–2021) ranged from 10.5 to 14.5 °C (Table S2). However, no significant interaction between pre-crop effects and air temperature based on the growing season (March to July) were found (Table S5). Conversely, significant interaction effects between pre-crops and annual rainfall (sum of precipitation during growing season from 1983–2021) were observed in winter wheat ($p = 0.027$) and spring barley ($p = 0.048$). However, no significant interaction effects ($p = 0.999$) were detected in winter rye (Table S5).

The result of the principal component analysis among pre-crops and rainfall showed that PC1 contributed 18.9 % and PC2 17.4 % to the variance in the grain yields of subsequent cereal crops over the ten decades. (Fig. 4). PC1 clearly separated three categorical levels of rainfall: wet (above the 75th percentile), normal (between the 25th and 75th percentiles), and dry (below the 25th percentile). The analysis revealed a linear trend of increasing that the influence of pre-crops and dry conditions on cereal grain yields increased during the experiment, compared to normal and wet conditions (Fig. 4). Consequently, in dry years, the impact of green fallow was higher particularly for winter wheat and spring barley, as it compensates for yield deficiency. But no significant differences were observed in winter rye (Figure S2), which may be related to the better drought tolerance of winter rye compared to winter wheat and spring barley. Furthermore, the differences among pre-crops were greater for winter wheat than for spring barley and winter rye in both dry and wet conditions, with this effect being more pronounced under dry conditions. In dry years, green fallow led to higher grain yields in winter wheat and spring barley compared to oat and maize. However, this effect was similar to that of bare fallow for winter wheat and to field bean for spring barley (Figure S2). In normal and wet years, green fallow resulted in higher grain yields in winter wheat compared to oat and maize, but no such effect was observed for winter rye or spring barley. During wet years, field bean and bare fallow produced similar increases in grain yields of winter wheat as green fallow. Additionally, in normal years, field bean had a similar effect on winter wheat grain yields as green fallow.

4. Discussion

4.1. Green fallow (clover mulch) and grain legume (field bean) increase grain yields in the immediate subsequent wheat crop

Based on the long-term data presented here, hypothesis (H1) can be confirmed: rotating green fallow as a pre-crop in terms of clover mulch improves the yield performance of the immediate subsequent cereal crops in this case winter wheat. However, this benefit does not extend to the grain legume pre-crop (field bean), which shows no yield advantage over bare fallow in the following cereal crop. Furthermore, green fallow (clover mulch) as a legume pre-crop not only improves the yield of the 1st subsequent cereal crop (winter wheat) but also positively influences the 2nd (winter rye) and 3rd cereal crops, supporting hypothesis H2.

A major factor driving yield increases after green fallow is the effective management of organic and mineral nitrogen (Ladha et al., 2022; Lacey et al., 2020). Long-term use of green fallow and mineral N fertilization increased nitrogen accumulation in soil and crop biomass, with winter wheat showing significant yield gains after five rotation cycles (1983–1999) (Lacey et al., 2020; Vaziritabar et al., 2024). Notably, wheat following clover mulch and receiving only half the recommended N rate achieved yields comparable to full-rate fertilization while reducing N leaching (Ladha et al., 2022). In contrast, field bean had limited impact under high N input (Vaziritabar et al., 2024). These differences are linked to residue C:N ratios. This can be explained by the fact that clover mulch (24:1) decomposes faster and releases N more efficiently than residues with wider ratios like oat (109:1), maize

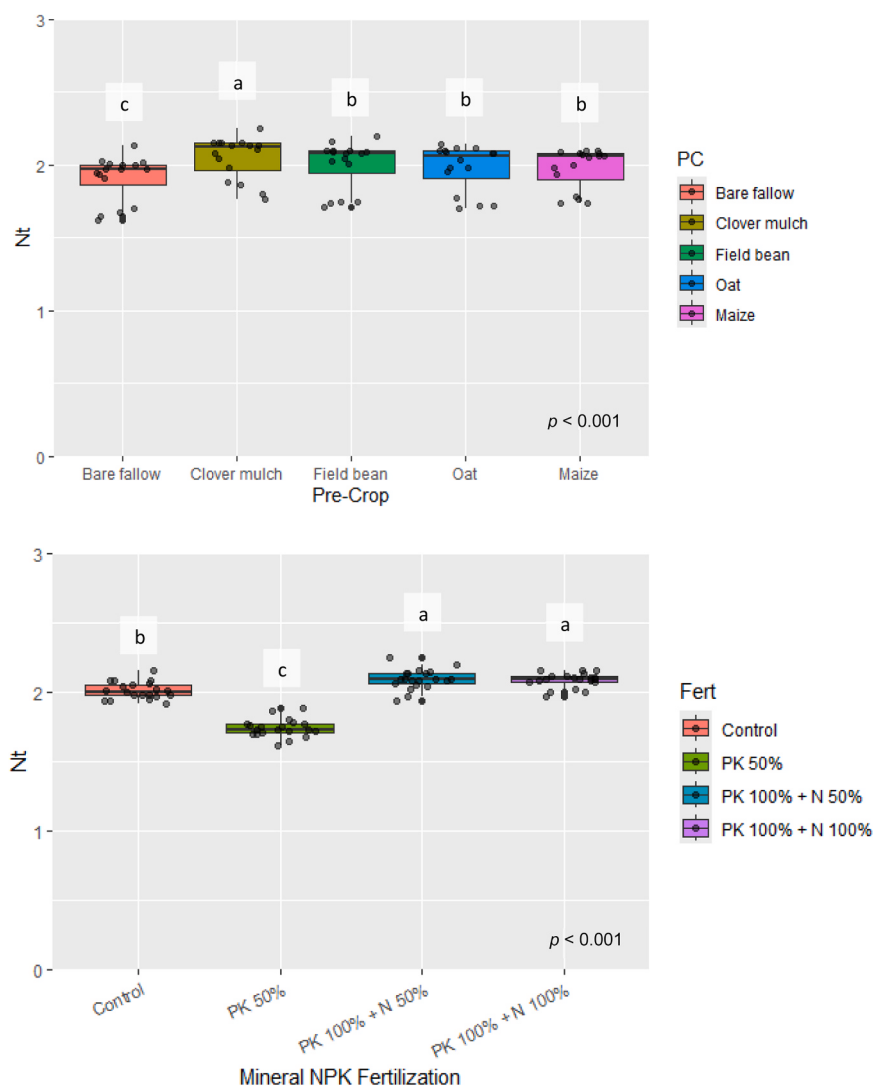


Fig. 2. Mean values of total N content (g kg⁻¹) of the soil (0–30 cm) depending on pre-crops and mineral NPK fertilization in biological N fixation trial from 2015 to 2021 (within 9th and 10th crop rotation) at Weilburger Grenze Giessen. Compact letters indicate significant differences between mean values.

(95:1), or field bean straw (30:1), which slow N mineralization (USDA–NRCS, 2011; Triberti et al., 2016; Malhi et al., 2011).

Long-term results confirm a synergistic NPK effect of green fallow on the immediate subsequent crop (winter wheat), supporting H3. In contrast, field bean showed no such effect compared to bare fallow, even in the 1st, 2nd, or 3rd subsequent crops. It is assumed that over 40 years, field bean's yield effect matched that of bare fallow, likely due to nitrogen removal through harvested grain (Vaziritabar et al., 2024). This highlights the importance of both the quantity and quality of plant residues in regulating soil nitrogen dynamics (Lacey et al., 2020; Powlson et al., 2011). Decomposing residues, particularly roots, can improve soil fertility in the long term by increasing nitrogen availability and promoting plant growth (Cherr et al., 2006; Lassaletta et al., 2014). In the current LTE, green fallow (clover mulch) outperforms other pre-crops due to its higher crop residue production compared to field beans, fallow, oats, and maize. These greater residue amounts contribute to increased nutrient inputs, especially nitrogen into the soil, a finding supported by other studies (Franzluebbers et al., 2020; Flohr et al., 2024).

Nitrogen cycling from crop residues is driven by soil microorganisms reliant on the carbon pool (Lacey et al., 2020). Therefore, the limited organic matter restricts their ability to immobilize excess inorganic N, often resulting in losses under conventional farming (Tonitto et al.,

2006). It should therefore be emphasized that including legumes and green manures in rotations enhances nitrogen recovery into soil organic matter, reduces leaching, and significantly lowers N losses compared to the 45–55 % typically lost in conventional systems (Ladha et al., 2022; Peoples et al., 2017; Drinkwater and Snapp, 2005). Based on our results and supported by previous findings, we conclude that crop diversification with green fallow (crimson clover, hairy vetch) enhances crop-soil ecosystem health, while promoting sustainability and climate resilience in rotational systems.

4.2. Bare fallow is inferior to the legume pre-crops (green fallow and field bean) and has a similar pre-crop effect to the cereal crops (maize and oats)

Based on the available data, hypothesis (H4) can be confirmed. Bare fallow has a significantly weaker pre-crop effect than green fallow. Its impact on the first subsequent crop is similar to field bean but tends to be worse for the second and third crops, aligning more closely with oats and maize. Some positive effects of bare fallow may result from weed suppression via tillage (Nielsen and Calderón, 2011), improved residue mineralization, reduced soil compaction, and better soil aeration (Gan et al., 2015). Additionally, bare fallow can enhance water storage and nitrate availability, as shown in a multi-site study by Nielsen and Calderón (2011).

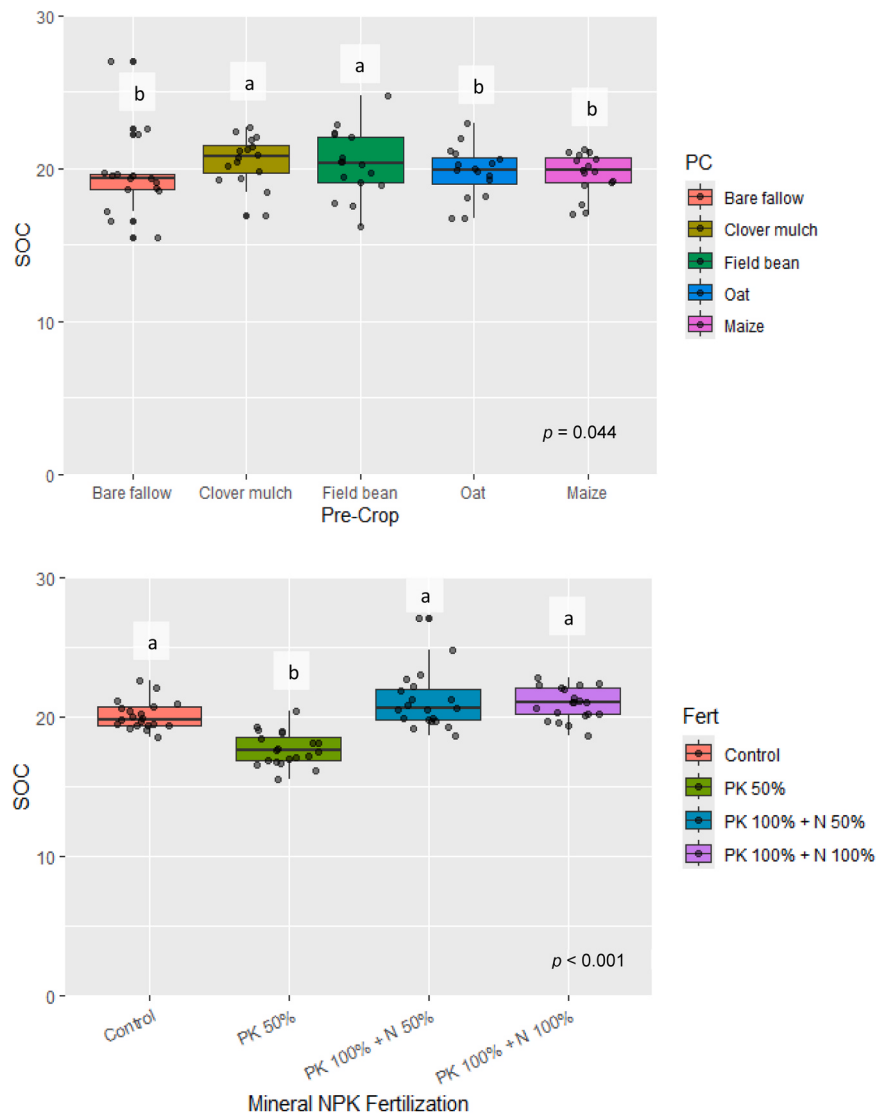


Fig. 3. Mean values of SOC content (g kg^{-1}) of the soil (0–30 cm) depending on pre-crops and mineral NPK fertilization in biological N fixation trial from 2015 to 2021 (within 9th and 10th crop rotation) at Weilburger Grenze Giessen. Compact letters indicate significant differences between mean values.

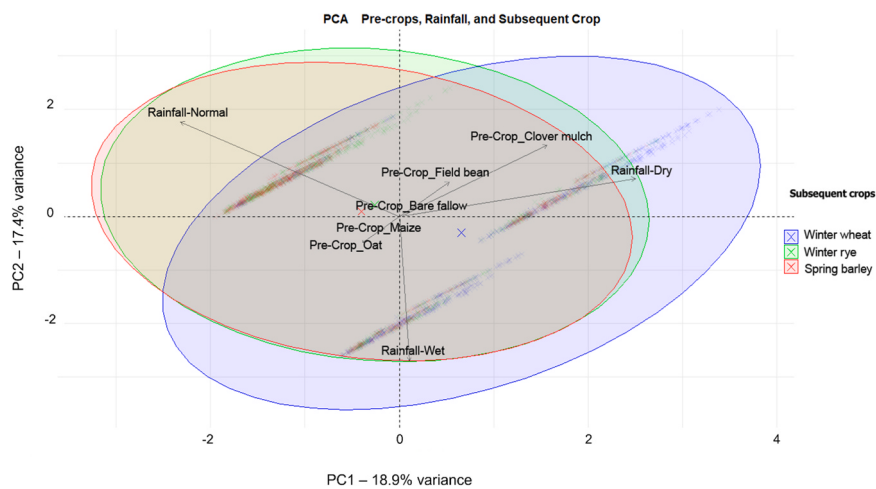


Fig. 4. Principle component analysis of pre-crops and rainfall on grain yield of subsequent cereal crops. Confidence ellipses are shown for winter wheat (1983–2019), winter rye (1984–2020) and spring barley (1985–2021).

Campbell et al. (2008) found that summer fallow increases net N mineralization compared to cropped land when water is sufficient. Similar findings were observed in our LTE, where the N balance in cereal rotations was up to 30 % higher than in bare fallow systems, which allow only a short period for residue mineralization (Vaziritabar et al., 2024). As a result, the benefits of bare fallow are comparable to fertilized pre-crops like oat and maize, suggesting that nitrogen from leaching or plant uptake is often unavailable to subsequent crops (Vaziritabar et al., 2024; Silgram and Chambers, 2002). However, the positive effects of bare fallow did not persist into the second (winter rye) and third (spring barley) crops, likely due to declining soil organic carbon and increased nitrogen leaching over time.

4.3. Effect of cereal pre-crops (oats, maize) on subsequent crops

In the current LTE, the poor performance of the cereal pre-crops (oats and maize) in terms of their effect on the yields of the subsequent crops mainly reflects the low quality of crop residues (lower N content), compared to green manure (Vaziritabar et al., 2024; Wang et al., 2021; Triberti et al., 2016). This has already been demonstrated in a previous study conducted in the current LTE. Here it was found that the incorporating crimson clover as green fallow adds an average of 116.4 kg N ha⁻¹ to the soil, while oat, maize and field bean only 25.4, 35.3 and 21.7 kg N ha⁻¹, respectively, were available for the following main crop (Vaziritabar et al., 2024). In line with this, a meta-analysis from several LTEs found that the crop yield followed by a non-legume cover crop under recommended fertilizer levels did not differ significantly from the yield after bare fallow land or was only 3 % lower (Tonitto et al., 2006).

Other LTEs have also shown that incorporation of straw into the soil in cereal crop rotations can lead to a downward trend in total soil N (Lafond et al., 2009; Malhi et al., 2011). This effect can be explained by the higher C:N ratio in cereal pre-crops, which leads to increased microbial immobilization of mineral nitrogen (NH₄⁺, NO₃⁻). This immobilized N pool is only available to subsequent crops to a limited extent, as it is released slowly and late through mineralization and cannot meet the N requirements of the subsequent crop during the phase of highest nutrient uptake (Cao et al., 2021). Further reasons for low yields in pure cereal rotations compared to diversification with legumes are due to soil-borne diseases caused by saprophytic pathogens as well as increasing weed pressure, particularly from wild grass species (Bateman, et al., 1998; Jenkyn et al., 2001; Peters et al., 2003). Further on, the propagation of cereal-specific nematodes (*Heterodera avenae*) can also have a negative effect on this unbalanced crop rotation (Smiley et al., 2005).

Against this background, it can be concluded that a pure cereal crop rotation provides lower functional richness with a single trait to the crop-soil ecosystem. This leads to crop rotational diseases and in increase in pests and weeds and thus to a negative impact on yield sustainability and reduced climate resilience (Costa et al., 2024; Smith et al., 2023; Macholdt et al., 2020).

4.4. Impact of climatic conditions on pre-crop effects

In the current LTE, legume preceding crops (especially clover mulch) led to higher winter wheat and spring barley yields, particularly in dry years. This effect can be explained by improved soil structure (including better soil aeration) and water retention capacity for subsequent crops, due to increasing soil organic matter (Lal, 2020; Kuht et al., 2022). In addition, it is assumed that these effects are also caused by C enrichment in the subsoil. This assumption is supported by a study conducted in the same LTE, which found a C increase by clover mulch of 4.1 % per annum down the full meter of soil (Hobley et al., 2018). This improvement in soil health can lead to a significant boost in yield, where the most of rainfall occurs in the fall through spring. In this context, Joyce et al. (2002) showed that using common hairy vetch or clover as a winter cover crop significantly increases the soil moisture content to one meter

depth compared with bare fallow. In addition, the use of winter cover crops (red clover) in rotation with maize increases water storage porosity along with plant available water (Jiang et al., 2007). Similar effects were also found in another study, where the incorporation of crimson clover residues into the soil maintain water content for longer duration than surface applied residues due to the greater microbial colonization and saprophytic fungi's than cereal cover crops (Thapa et al., 2022). Another reason why clover mulch has led to higher yields in dry years could be the soil microbial populations, whose growth and activity are promoted by cover crops (Kuht et al., 2022; Hueso et al., 2011). It has been proven that microbial communities interact with plant roots and thus have a positive impact on crops through growth-promoting and pathogen-suppressing effects (Inceoglu et al., 2013).

Furthermore, wheat yield depends not only on the growing season precipitation but also on the amount of water stored in the soil in the fallow season in dryland cropping systems (Yu et al., 2025). Conversely, in regions with insufficient rainfall, using green fallow (such as clover mulch) may negatively affect the soil's water supply for the subsequent crop (Nielsen and Vigil, 2005).

Further on it is well known that the impact of weather is highly associated with the soil texture and organic matter. For example, wheat yields in dry years are higher on clay soils compared to silt loam and sandy soils, indicating that wheat grown on clay soil has higher drought tolerance than that grown on silt loam (He et al., 2014). On the other hand, in wet years, oxygen deficiency can occur on clay soils due to waterlogging, which can lead to yields losses (Li et al., 2019).

A key strength of this study is its over 40 years of long-term management comparing green and bare fallow, offering valuable insights into the lasting impacts of land-use practices on cereal crop productivity under changing climate conditions. The LTE employed various pre-crops (maize, oats, field bean, clover, bare fallow) within a four-year rotation, resulting in differing levels of crop rotation biodiversity.

However, one limitation of this study is that crop diversification is limited, especially in cereal-only rotations, which restricts the diversity of functional traits (Smith et al., 2023). Therefore, future LTEs should include broadleaf species like *Asteraceae* and *Brassicaceae* to enhance functional richness and better assess biodiversity's impact on yield sustainability and climate resilience. Another limitation concerns straw and residue management: while clover biomass was fully returned as green fallow, only harvest residues remained from maize, oat, and field bean. Additionally, data on below-ground biomass and root N content are lacking, leaving uncertainty about the nitrogen available to subsequent crops. Variations in residue decomposition rates due to differing N concentrations among pre-crops further complicate understanding of nutrient cycling.

5. Conclusion

Our long-term study shows that green fallow (e.g., crimson clover, hairy vetch) in rotations boosts the yield of the immediate subsequent cereal crop, especially winter wheat, with benefits extending to the second (winter rye) and third cereal crops. This advantage was not seen with grain legumes, where green fallow and bare fallow had similar effects. In addition, green fallow also enhanced the efficiency of mineral NPK fertilization. For example, winter wheat following clover mulch achieved comparable yields with only half the recommended N fertilizer rate, reducing nitrogen leaching and promoting environmental sustainability. In contrast, bare fallow had a poorer pre-crop effect than green fallow, comparable to legumes for the first crop but worse for subsequent ones. We conclude that rotations including at least two functional groups, particularly legume pre-crops, improve grain yield and climate resilience, while continuous cereal or bare fallow rotations reduce yield and sustainability.

CRediT authorship contribution statement

Bernd Honermeier: Writing – review & editing, Visualization, Validation, Supervision, Project administration, Funding acquisition. **Michael Frei:** Writing – review & editing, Visualization. **Yavar Vaziritabar:** Writing – review & editing, Writing – original draft, Formal analysis, Data curation. **Janna Macholdt:** Writing – review & editing, Visualization, Validation.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Prof. Dr. Bernd Honermeier reports financial support was provided by German Federal Ministry of Education and Research (BMBF). If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Compliance with ethical standards

The authors declare no conflict of interest.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.eja.2025.127765](https://doi.org/10.1016/j.eja.2025.127765).

Data availability

Data will be made available on request.

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