



Faba bean and spring barley in sequence with catch crops: Grain yields and nitrate leaching

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ABSTRACT

Context/Problem: Importing protein into Europe is causing sustainability challenges, which has resulted in an increasing European interest in locally growing faba bean as a protein source. There is, however, a concern that this may result in higher nitrate leaching compared with conventional cereal-based systems.

Objective/Research question: We investigated the risk of nitrate leaching and its mitigation strategy after growing faba bean with catch crops within a conventional European cropping system that also includes catch crops in spring barley.

Methods: We conducted a field experiment with faba bean (*Vicia faba* L.) and three catch crops (chicory (*Cichorium intybus* L.), perennial ryegrass (*Lolium perenne* L.) and winter rye (*Secale cereale* L.)) grown in sequence with spring barley (*Hordeum vulgare* L.) and replicated in time over a period of three years. Continuous spring barley with catch crops (perennial ryegrass and fodder radish (*Raphanus sativus* L.)) were used as a reference. Measurements included grain yield and grain nitrogen (N) of the main crops, aboveground biomass and N yield of the catch crops, and nitrate leaching.

Results: Grain yield and grain N of faba bean grown with undersown catch crops were not statistically different than without catch crop and post-harvest sown catch crops. Catch crops with faba bean had lower aboveground biomass and N yield than with spring barley. Faba bean as pre-crop compensated for the reduced amount of fertilizer input and also increased the grain yield and grain N of the subsequent spring barley. In 2020–21, nitrate leaching from both spring barley and faba bean without catch crops was not statistically different, with an average of 64 kg NO₃-N ha⁻¹. In contrast, in 2021–22, nitrate leaching after faba bean without catch crops was higher with 104 kg NO₃-N ha⁻¹, compared with spring barley with 68 kg NO₃-N ha⁻¹. Catch crops significantly reduced nitrate leaching on average by up to 55 kg NO₃-N ha⁻¹ from faba bean and 62 kg NO₃-N ha⁻¹ from spring barley fields.

Conclusions: The study reveals that growing faba bean can reduce N fertilizer input without compromising the grain yield and grain N of following spring barley. Variable nitrate leaching between years from faba bean requires more research on diverse pedo-climatic and agronomic conditions to better assess nitrate leaching risks and reduction strategies.

Implications or significance: These results will aid in designing cropping systems including faba bean and catch crops combinations to reduce N fertilizer input and nitrate leaching risks and improve protein sufficiency.

1. Introduction

Despite ecosystem services and health benefits for humans and livestock, legumes at present are underused in most Western countries (Foyer et al., 2016). In 2020 and 2021, the global average of the arable area under grain legumes was ~ 15% compared to ~ 5% in Europe

(FAOSTAT., 2023). The low arable area of grain legumes in Europe has been consistent over many decades owing to specialization, market competitiveness, lower yield stability, and lack of evidence of the benefits of legumes in a cropping system (Zander et al., 2016). As a consequence, Europe imports 70% of protein, primarily soybean, from other regions to meet the demand for human and livestock consumption

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(Watson et al., 2017). The large import of soybean as a source of protein has caused a widespread indigenous deforestation, and a consequent collapse of ecosystem carbon stocks (Ptak et al., 2020). A global concern of sustainability and degradation of the environment in soybean exporting countries has propelled a growing interest in cultivating grain legumes locally in Europe as sources of protein. This could improve protein sufficiency and promote more sustainable agricultural systems in Europe by increasing nitrogen (N) supply through biological fixation, reducing external N fertilizers, offering break crop effect, and increasing biodiversity and crop diversification (Köpke et al., 2010; Preissel et al., 2015; Watson et al., 2017). Grain legumes such as faba bean (*Vicia faba* L., also known as broad bean and horse bean) were part of traditional cropping systems and played a crucial role in maintaining and improving soil N fertility through atmospheric N fixation. Faba bean has the highest dependence on N fixation for growth compared with other major cool-season grain legumes (Hauggaard-Nielsen et al., 2012). Although faba bean as a pre-crop (main crop in the previous year) can reduce N fertilizer requirement to the following crop (Jensen et al., 2010), its inclusion in the European cropping systems is debatable because of the risk of increased N leaching (Reckling et al., 2020), associated with the mineralisation of its N rich residues (Neugschwandtner et al., 2015).

Over the last decade from 2010 to 2021, there has been a notable rise in faba bean cultivation area from 2.8 to 3.0 million ha globally and from 4.2 to 7.1 hundred thousand ha in Europe (FAOSTAT., 2023). As a result, faba bean now in 2021 covers approximately 15% of the total area under grain legumes in Europe, whereas soybean occupies the largest area with 28% (FAOSTAT., 2023). The increasing trend of cultivating faba bean in Europe necessitates the evaluation and quantification of its residual value on the following crop to optimise fertilisation rates and assess associated concerns with its environmental risks of nitrate leaching compared with conventional cereal-based cropping systems.

Growing catch crops (also called cover crops) post-harvest of the main crops to take up N is one of the preferred practices to reduce nitrate leaching during autumn and winter, and compulsory in many European countries such as Denmark, France, and Netherlands and are being promoted in Norway, Sweden, and Finland (Thomsen and Hansen, 2014; Aronsson et al., 2016; Komainda et al., 2016; Kathage et al., 2022; Kumar et al., 2023). The efficiency of catch crops to take up high amounts of N, reduce nitrate leaching, and have high residual value with high amounts of N transferred to the subsequent crop depends on several factors which are important for designing an efficient cropping system. These are (1) duration of catch crop growth: the type of main crop and harvest time, for example late harvest of faba bean compared to spring barley (*Hordeum vulgare* L.), will affect the duration of favorable environmental conditions for catch crop growth and their ability to reduce nitrate leaching and N uptake (Pullens et al., 2021; Kumar et al., 2023); (2) type of catch crop: with different canopy and root characteristics biomass and N accumulation can be variable in catch crops (Thorup-Kristensen et al., 2003); (3) strategy of catch crop sowing: undersown catch crops within the main crop can be affected by the competition for resources from the main crop (Burger et al., 2017; Doltra and Olesen, 2013) compared to post-harvest sown catch crops (Berntsen et al., 2006; Constantin et al., 2011). How duration of the catch crop (number 1), different catch crops (number 2), and their sowing strategy (number 3) in combination with faba bean affect the yields and nitrate leaching is less explored. This is of agronomic significance as the farmers need to adjust and delay the catch crop sowing when the main crop is faba bean (longer maturity duration) compared to when the main crop is a cereal with shorter maturity duration, such as spring barley (number 1).

In this study, we investigated the impact of incorporating faba bean into a conventional cereal-based cropping system with catch crops over three seasons (from 2020–21 to 2022–23). The study had two primary objectives: 1) evaluate the grain yield of faba bean and spring barley

grown with undersown and post-harvest sown catch crops (perennial ryegrass (*Lolium perenne* L.), chicory (*Cichorium intybus* L.), winter rye (*Secale cereale* L.), and fodder radish (*Raphanus sativus* L.)) in comparison to cultivation without catch crops, and 2) evaluate the effect of catch crops in reducing nitrate leaching from faba bean compared to nitrate leaching from spring barley grown with catch crops.

2. Materials and methods

2.1. Study site

The experiment was carried out at Foulum (56.30°N, 9.35°E) on a sandy loam classified as a Mollic Luvisol according to the WRB (FAO) system (Krogh and Greve, 1999). The soil (25 cm depth) has 9.9% clay (<2 µm), 11.5% silt (2–20 µm), 41.5% fine sand (20–200 µm), and 34.5% coarse sand (200–2000 µm), and organic carbon content of 1.5% (determined on ball-milled subsamples using high-temperature dry combustion; Thermo Flash 2000 NC Soil Analyzer, Thermo Fisher Scientific, Waltham Massachusetts, USA).

Average temperature, global radiation, potential evapotranspiration, and precipitation data were obtained from an online grided database maintained by the Aarhus University for Foulum research station (<http://agro-web01t.uni.au.dk/klimadb/>). Precipitation was measured at 1.5 m height and corrected to the soil surface according to Allerup et al. (1998). The first two months of 2021 and December of 2022 were colder with more days of negative average temperature than in other years (Fig. 1). Global radiation was higher in May to July in 2020 than in 2021 and 2022. Precipitation from August to February was highest in 2022–23 and lowest in 2020–21. Monthly average temperature during the experimental periods from March 2020 to April 2021, from May 2021 to April 2022, and from May 2022 to April 2023 ranged from 8.1 to 9.1 °C. The sums of corrected precipitation to the soil surface were 795 mm, 935 mm, and 918 mm, potential evapotranspiration sums were 731 mm, 606 mm, and 634 mm for the three corresponding experimental periods, and the average of monthly sums of global radiation were between 296 and 319 MJ m⁻² d⁻¹. The comparative normal of long-term (1991–2020) average temperature and sums of corrected precipitation to the soil surface were 7.7 °C, 8.2 °C, 8.2 °C and 925 mm, 820 mm, and 820 mm, respectively, for the three corresponding experimental periods.

2.2. Field experiment

The experiment was established in the spring of 2020 in plots of 3 m wide and 15 m long. The experimental site was previously grown with cereals. An experiment with faba bean and three catch crops (chicory, perennial ryegrass and winter rye) were grown in sequence with spring barley and replicated in time over a period of three years. Continuous spring barley with catch crops (perennial ryegrass and fodder radish) were used as reference. Thus, there were 11 cropping sequences in the experiment (Table 1), and each was arranged in four blocks with randomised complete block design. Four treatments were seeded with faba bean as the main crop in 2020 at the rate of 226–288 kg ha⁻¹ with a row distance of 24 cm, and seven other treatments were seeded with main crop spring barley at the rate of 162–177 kg ha⁻¹ with a row distance of 12 cm. In 2021, the four treatments previously seeded with faba bean were seeded with spring barley, and the four treatments previously seeded with spring barley were seeded with faba bean. The remaining three treatments grew spring barley for the whole experimental period. In 2022, all treatments were seeded with spring barley as the main crop.

Field operations with the dates are presented in Table 2. Sites were ploughed to ca. 20 cm depth. After plowing, NPK fertilizers were applied to plots with faba bean and spring barley at the rates presented in Table 1. The spring barley received N according to the recommended rate, but after faba bean or catch crops rates were reduced by 30 kg N ha⁻¹ to account for the residual value, due to N transfer from their

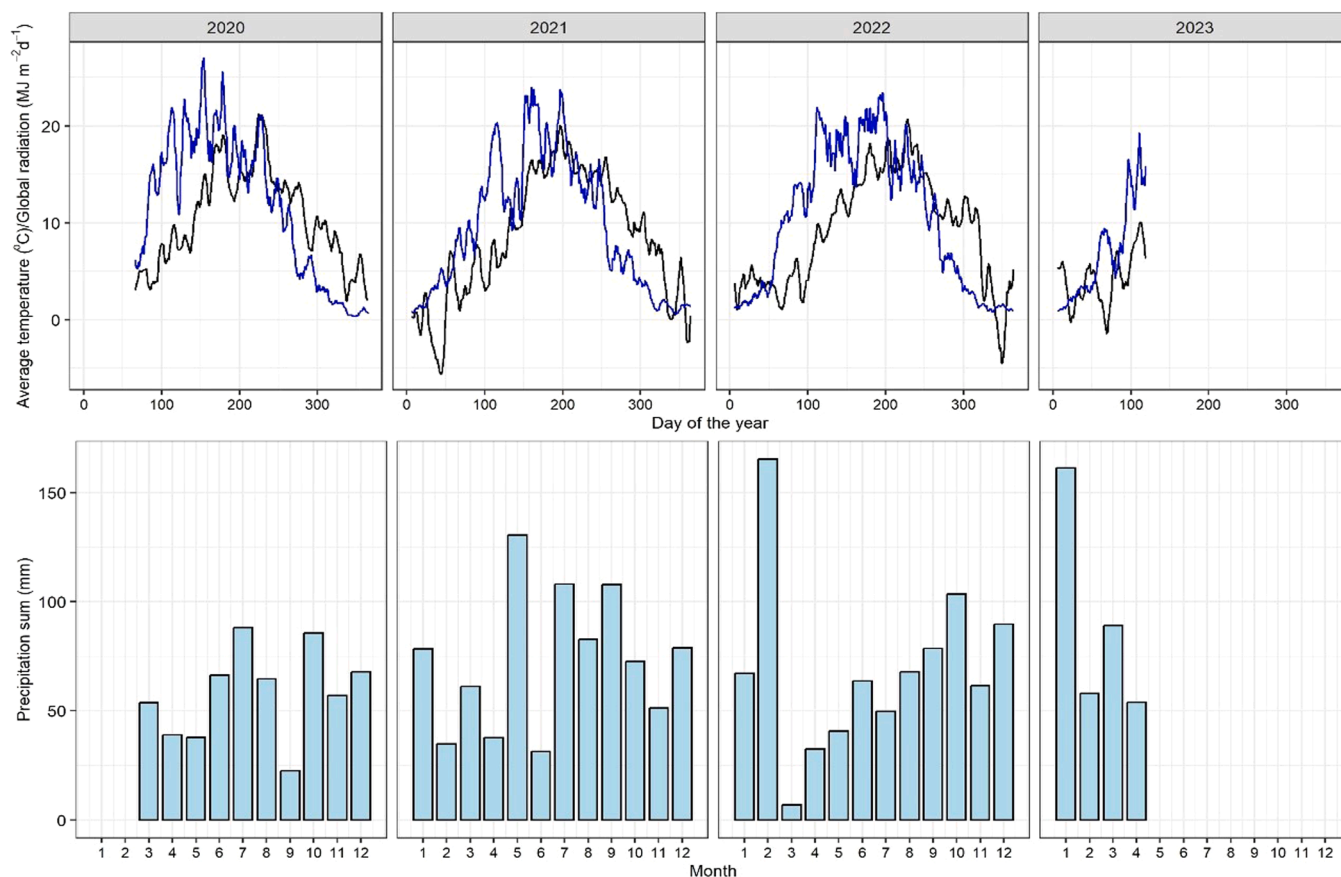


Fig. 1. A seven-day moving mean of average temperature (above panel, black line) and global radiation (above panel, blue line), and monthly precipitation sum (bottom panel, corrected to the soil surface) in the experimental period.

Table 1

Overview of crop sequence and N, phosphorous (P), and potassium (K) applications for faba bean (FB) and spring barley (SB) followed by bare soil or undersown catch crops (CC) of perennial ryegrass (g), chicory (c), or post-harvest sown winter rye (w) or fodder radish (f). Treatment considers the whole sequence of main crop/CC combination that changes over the years, while the main crop/CC describes the treatment within each year.

Treatment	2020		2021		2022	
	Main crop/CC	N/P/K (kg ha ⁻¹)	Main crop/CC	N/P/K (kg ha ⁻¹)	Main crop/CC	N/P/K (kg ha ⁻¹)
1	FB	0/25/131	SB	128/24/61	SB	155/21/59
2	FB/g	0/25/131	SB/g	128/24/61	SB/g	125/21/59
3	FB/c	0/25/131	SB/g	128/24/61	SB/g	125/21/59
4	FB/w	0/25/131	SB/g	128/24/61	SB/g	125/21/59
5	SB	158/30/75	FB	0/25/131	SB	125/21/59
6	SB	158/30/75	FB/g	0/25/131	SB/g	125/21/59
7	SB	158/30/75	FB/c	0/25/131	SB/g	125/21/59
8	SB	158/30/75	FB/w	0/25/131	SB/g	125/21/59
9	SB	158/30/75	SB	158/30/75	SB	155/21/59
10	SB/g	158/30/75	SB/g	128/24/61	SB/g	125/21/59
11	SB/f	158/30/75	SB/f	128/24/61	SB/f	125/21/59

residues to the spring barley.

In spring barley, perennial ryegrass was undersown 11–16 days after spring barley sowing while fodder radish was sown 1–20 days after the barley harvest (Table 2). Weed was controlled by herbicides in spring barley (see Supplementary Table 1 for the ingredient and date of application) and by tine cultivation in faba bean in all years. In faba bean catch crops of perennial ryegrass (*Lolium perenne* L.) and chicory (*Cichorium intybus* L.) were undersown after the last tine cultivation. The undersown catch crops in spring barley and faba bean were sown with a traditional sowing machine (a Nordsten Seed Drill). The catch crop of winter rye (*Secale cereale* L.) was sown 1–3 days after faba bean was harvested. The aimed seeding rate of catch crops were 12 kg ha⁻¹, 20 kg ha⁻¹, 3 kg ha⁻¹, and 90 kg ha⁻¹ for perennial ryegrass, fodder radish, chicory, and winter rye, respectively. Plots without catch crops were sprayed with herbicide in autumn to keep the soil bare.

In each plot of the four blocks, two suction cups (length 68 mm, diameter 20 mm, and 0.1 MPa air entry value, type K 100, UMS GmbH) were installed at a depth of 1 m in the middle of the plot, and with a distance of 5 m between them to collect soil water for nitrate-N (NO₃-N) analysis.

Spring barley and faba bean were harvested with a Haldrup plot harvester (1.5 m wide). Spring barley straw was removed without determining aboveground biomass, while the faba bean straw was chopped and left on the plots. Plant material of catch crops was sampled on 22 and 21 October in 2020 and 2022, and 8 November in 2022 from a predetermined area of 0.5 m².

2.3. Measurements

Harvested grain of main crops and plant samples of catch crops (into

Table 2

Field operations in faba bean (FB) and spring barley (SB) during three experimental periods.

	2020–21	2021–22	2022–23
Ploughing 20–22 cm	25 Mar	29 Mar	31 Mar
Rotovator medium intensity	26 Mar	16 Mar	17 Mar
PK fertilizer application FB	26 Mar	31 Mar	-
NPK fertilizer application SB	27 Mar	30 Mar	5 Apr
FB sowing	27 Mar	31 Mar	-
SB sowing	30 Mar	30 Mar	11 Apr
Rolling	2 Apr	7 Apr	12 Apr
Perennial ryegrass sowing in SB	14 Apr	15 Apr	22 Apr
Tine cultivation in FB	17 Apr, 29 Apr, 13 May	15 Apr, 11 May, 28/31 May	-
Chicory and ryegrass sowing in FB	13 May	28 May	-
Chemical weed control in SB	7 May	19-May	19 May
Irrigation (all plots)		25 Jun (23 mm)	
Harvest SB	11 Aug	12 Aug	10 Aug
Fodder radish sowing after SB	12 Aug	20 Aug	30 Aug
Harvest FB	25 Aug	8 Sep	-
Winter rye sowing after FB	28 Aug	9 Sep	-
Glyphosate application in bare autumn soil	17 Sep	8 Sep	1 Sep, 12 Oct
Plant sampling	22 Oct	21 Oct	8 Nov
Soil water collection	8 Oct	14 July	13 Oct
	2020–29 Mar 2021	2021–17 Mar 2022	2022–14 Apr 2023

two fractions; one with catch crops and the other with weeds and volunteers) were dried and weighed for grain yield and aboveground biomass measurements. Grain N of the main crop and N yield of the catch crops were analyzed by dry combustion at 950°C using Vario Max Cube. Soil water samples from the plots were collected approximately every two weeks during the periods of percolation (Table 2). Three days before soil water sample collection a suction of 60–70 kPa was applied to the sampling device. Samples from the two suction cups in each plot were mixed in equal aliquots, frozen shortly after sample collection, and subsequently analyzed for nitrate on a Technicon Auto Analyzer (Tarrytown, NY, USA). Daily percolation from the root zone was estimated using the model Evacrop (Olesen and Heidmann, 1990) which takes into account daily inputs of potential evapotranspiration, temperature, and precipitation as measured by a nearby meteorological station. Percolation-weighted daily nitrate concentrations were computed between the soil water collection dates and multiplied with the respective calculated daily percolation amount to obtain daily N leaching amounts. Cumulative daily nitrate leaching from 8 October 2020–30 June in 2021, 1 July 2021–30 June in 2022, and 1 July 2022–14 April in 2023, for the drainage periods 2020–21, 2021–22, and 2022–23, respectively, was used for statistical analyses.

2.4. Statistical analysis

All statistical analyses were conducted in R version 4.3 (R core team, 2023). Unless otherwise specified, we used linear mixed effect models using the function lmer (in package lme4, Bates et al., 2015) with Satterthwaite approximation for degrees of freedom (package lmerTest, Kuznetsova et al., 2017). The analyses for main crop were conducted on the effect of treatments (Table 1) on grain yield and grain N. Each main crop was analysed differently: For spring barley, analyses were conducted separately for each experimental year, and the models were constructed with treatment (Table 1) as a fixed effect and block as a

random effect. For faba bean, Treatments 1–4 in 2020 were considered equivalent to treatments 5–8 in year 2021. The models were thus constructed with catch crop treatment (none, perennial ryegrass, chicory, or winter rye) and year, as well as the interaction between the two as fixed effects, and block as a random effect. The interaction effect was assessed through likelihood ratio tests between nested models, and eliminated from the final model when not significant at a threshold of $p = 0.05$. Analyses for catch crops were conducted on aboveground biomass and N yield separately for each experimental year and the statistical models included the same fixed and random effects as for the analyses of grain yield and grain N for spring barley. However, aboveground biomass in the year 2021 was modelled with a constant variance function (varIdent, package nlme, Pinheiro et al., 2023) to account for differing variances between treatments. Due to non-normality, N yield was modelled using a generalized linear mixed effects model with a Gamma probability distribution and a log-link function (glmmTMB, Brooks et al., 2017). In the year 2021, five observations of N yield were missing due to a very small quantity for wet chemistry analysis. For nitrate leaching, all three drainage periods were analysed together using a generalized linear mixed effects model with Tweedie exponential error distribution and log-link function (glmmTMB). In all analyses, post hoc pairwise comparisons were performed using the emmeans package (Lenth., 2023) with the Kenward-roger method to compute the degrees of freedom, Bonferroni's method for confidence level adjustment, and Holm's method for p adjustment.

3. Results

3.1. Grain yield in main crops

Grain yield of faba bean was not statistically different when it was grown without catch crops and, with undersown catch crops of perennial ryegrass and chicory. The faba bean grain yield differed slightly but significantly between the two years, with a higher overall grain yield of $6.9 \pm 0.18 \text{ t ha}^{-1}$ in 2020, and $6.5 \pm 0.18 \text{ t ha}^{-1}$ in 2021. In contrast, the grain yield of spring barley was significantly affected by catch crops in all three experimental years (Table 3). With pre-crop faba bean in 2020, spring barley produced significantly higher grain yields in 2021 compared with pre-crop spring barley (Fig. 2), despite the reduction in N fertilization of 30 kg N ha^{-1} (Table 1). In 2022, with different main crops with and without catch crops in the two previous years, there was no clear effect on the yield of spring barley observed. In general, continuous spring barley with and without catch crops (treatments 9, 10, and 11) had the lowest grain yields, although not significantly different from the other treatments. Compared with continuous spring barley grown without catch crops, pre-crop faba bean increased the grain yields of spring barley on average by 1.0 t ha^{-1} in 2021 and 0.7 t ha^{-1} in 2022 (Fig. 2).

3.2. Grain N in main crop

Similarly to the grain yields, grain N of faba bean was not statistically different with and without catch crops, however, it differed between the years, with higher grain N in 2020 ($269 \pm 9.23 \text{ kg N ha}^{-1}$) than in 2021 ($246 \pm 9.23 \text{ kg N ha}^{-1}$) (Table 3). For spring barley, similar to the grain yield, grain N was higher with pre-crop faba bean compared with pre-crop spring barley in 2021 (Fig. 3). In 2022, no clear effects were observed. Compared with continuous spring barley grown without catch crops, pre-crop faba bean without catch crops compensated for the reduction of 30 kg N ha^{-1} fertilizer into following spring barley and increased grain N of spring barley on average by 9 kg N ha^{-1} in 2021 and 1 kg N ha^{-1} in 2022 (Fig. 3).

3.3. Aboveground biomass and N yield in catch crops

Aboveground biomass and N yield in the catch crops differed with

Table 3

Effect of treatments on grain yield (t DM ha^{-1}) and grain N (kg N ha^{-1}) of faba bean and spring barley, and aboveground biomass (t DM ha^{-1}) and N yield (kg N ha^{-1}) of catch crops, and nitrate leaching ($\text{kg NO}_3\text{-N ha}^{-1}$) from sequences of main crop and catch crop. *F* statistics presented with degrees of freedom in the brackets for analysis of variance of linear mixed models. Chi-Square (χ^2) statistics presented with degrees of freedom (df) and sample size (N) in the brackets for analysis of deviance for generalised linear mixed models.

Main crop/catch crop	Test value	<i>p</i> value	Year
Main crop			
Grain yield			
Faba bean	$F(3,24) = 2.93$	0.054	2020 & 2021 [#]
Spring barley	$F(6,18) = 2.91$	0.037	2020
Spring barley	$F(6,18) = 14.56$	<0.001	2021
Spring barley	$F(10,30) = 4.63$	<0.001	2022
Grain N			
Faba bean	$F(3,24) = 2.80$	0.062	2020 & 2021 ^{##}
Spring barley	$F(6,18) = 5.58$	0.002	2020
Spring barley	$F(6,18) = 7.16$	<0.001	2021
Spring barley	$F(10,30) = 3.00$	0.01	2022
Catch crop			
Aboveground biomass			
	$F(4,12) = 18.55$	<0.001	2020
	$F(7,21) = 26.69$	<0.001	2021
	$F(7,21) = 0.87$	0.547	2022
N yield			
	$\chi^2(\text{df}=4, N=20) = 34.44$	<0.001	2020
	$\chi^2(\text{df}=7, N=27) = 28.70$	<0.001	2021
	$\chi^2(\text{df}=7, N=32) = 29.57$	0.001	2022
Treatment (Table 1)			
Nitrate leaching			
Effect			
Treatment	$\chi^2(\text{df}=10, N=132) = 314$	<0.001	
Drainage period	$\chi^2(\text{df}=2, N=132) = 13$	0.001	
Treatment:Drainage period	$\chi^2(\text{df}=20, N=132) = 233$	<0.001	

[#] Years significantly different from one another: $F(1,24) = 5.51, p = 0.028$

^{##} Years significantly different from one another: $F(1,24) = 12.44, p = 0.002$

the main crop in all three experimental years (Table 3). Undersown perennial ryegrass and chicory, and post-harvest sown winter rye in faba bean had lower aboveground biomass and N yield compared with undersown perennial ryegrass and post-harvest sown fodder radish in spring barley both in 2020 and 2021 (Figs. 4 and 5). In 2022, with only spring barley as the main crop, aboveground biomass and N yields were not statistically different in the catch crops.

3.4. Nitrate leaching

Nitrate leaching was significantly affected by main crop and catch crop combinations, drainage period, and their interactions (Table 3). In the drainage period of 2020–21, nitrate leaching was not statistically different in faba bean with $67 \text{ kg NO}_3\text{-N ha}^{-1}$ and in spring barley with $63 \text{ kg NO}_3\text{-N ha}^{-1}$ without catch crops (Fig. 6). In 2021–22, nitrate leaching was higher in faba bean with $104 \text{ kg NO}_3\text{-N ha}^{-1}$ and spring barley with $68 \text{ kg NO}_3\text{-N ha}^{-1}$ without catch crops. In 2022–23, nitrate leaching was not statistically different in spring barley and catch crops combinations. In all three drainage periods, nitrate leaching was significantly reduced with catch crops grown within and after the main crops. Although nitrate leaching was reduced with catch crops after faba bean in the drainage period 2021–22, it was not statistically different from spring barley without catch crops. On average catch crops grown with faba bean reduced nitrate leaching by about $54 \text{ kg NO}_3\text{-N ha}^{-1}$ in the two drainage periods compared with faba bean without catch crops. Catch crops with spring barley reduced nitrate leaching on average by $54\text{--}62 \text{ kg NO}_3\text{-N ha}^{-1}$ with catch crops in the three drainage periods.

4. Discussion

4.1. Grain yield and grain N: main crop and catch crop combinations

Growing catch crops in autumn to take up N is a common practice in many European countries. Undersown catch crops can compete for resources with the main crop and can decrease the grain yield and grain N of the main crop (Burger et al., 2017; Munkholm and Hansen, 2012). In our study, grain yield and grain N were not statistically different when the main crop faba bean was without catch crops or had undersown perennial ryegrass during the growing season. This is consistent with the results of De Notaris et al. (2023), who suggested that faba bean outcompete undersown perennial ryegrass. Faba bean is known to have a competitive ability with vigorous early growth, greater plant height, larger leaf size, and green area index than many other leguminous crops (Karkanis et al., 2018; Shabbir et al., 2021). In our study catch crops grown with faba bean had lower aboveground biomass and N yield than those grown with spring barley, regardless of establishment method (undersown or post-harvest sown) and type of catch crop (chicory and fodder radish are from different families), (Figs. 4 and 5), verifying the competitive ability of faba bean with the undersown catch crops. Here this competitive ability of faba bean and its impact on the undersown perennial ryegrass was most likely linked with the delayed sowing of the undersown perennial ryegrass, approximately 47–58 days later than that of faba bean. In contrast, in the spring barley, undersowing of perennial ryegrass was only 11–16 days later. Thus, compared to spring barley, faba bean clearly had more time to develop and access resources ahead of the undersown catch crops. Furthermore, due to longer maturity, the later harvest of faba bean by 14–27 days than that of spring barley delayed the sowing of the post-harvest sown catch crops. This exposed the catch crops sown after the harvest of faba bean to less favorable growing conditions in autumn, consequently reducing their aboveground biomass and N yield compared with the aboveground biomass and N yield in the catch crop after spring barley (Kumar et al., 2023). The different types of post harvest catch crops sown with faba bean or spring barley might also have impacted the growth of the catch crops. From a perspective of faba bean production and quality, these results suggest that faba bean can be grown in sequence with undersown catch crops without compromising the grain yield and grain N.

Pairwise comparison indicated that the grain yield and grain N of spring barley with undersown perennial ryegrass or without catch crops varied in the experimental years. Regarding the pre-crop, the cultivation of spring barley following faba bean resulted in increased grain yields and grain N compared to a pre-crop of spring barley, and this was more pronounced in 2021 than in 2022. This shows the positive impact of pre-crop faba bean on the spring barley production and quality. In a review, Preissel et al. (2015) underlined a similar positive effect of grain legumes, including faba bean, with increased grain yield of approximately $0.72\text{--}1.47 \text{ t ha}^{-1}$ on the following cereals (with fertilization of $20\text{--}200 \text{ kg N ha}^{-1}$) across many European countries. In our study, the spring barley grain yield following faba bean increased within this range, averaging 0.85 t ha^{-1} in two years (with 125 kg N ha^{-1} of fertilization, Treatment 1 minus treatment 9 in 2021 and Treatment 5 minus treatment 9 in 2022). These increases can be explained by a higher amount of available N from the mineralization of N rich faba bean (Jensen et al., 2010; Neugschwandtner et al., 2015) and catch crop residues (Vogeler et al., 2023; Thomsen and Chirstensen., 1999). These increases also suggest that the availability of N from faba bean and catch crop residues exceeded the compensation for the 30 kg N ha^{-1} reduction in fertilizer input into spring barley grown after faba bean and catch crops. The results indicate that N fertilization can be reduced by incorporating faba bean into a conventional spring barley and catch crop cropping system. Apart from the reduction in N fertilization, inclusion of faba bean in a cereal-based cropping system, similar to other legumes, provides various ecosystem services, such as the “break-crop effect” to disrupt soil-borne disease cycles (Watson et al., 2017) and reduces pest

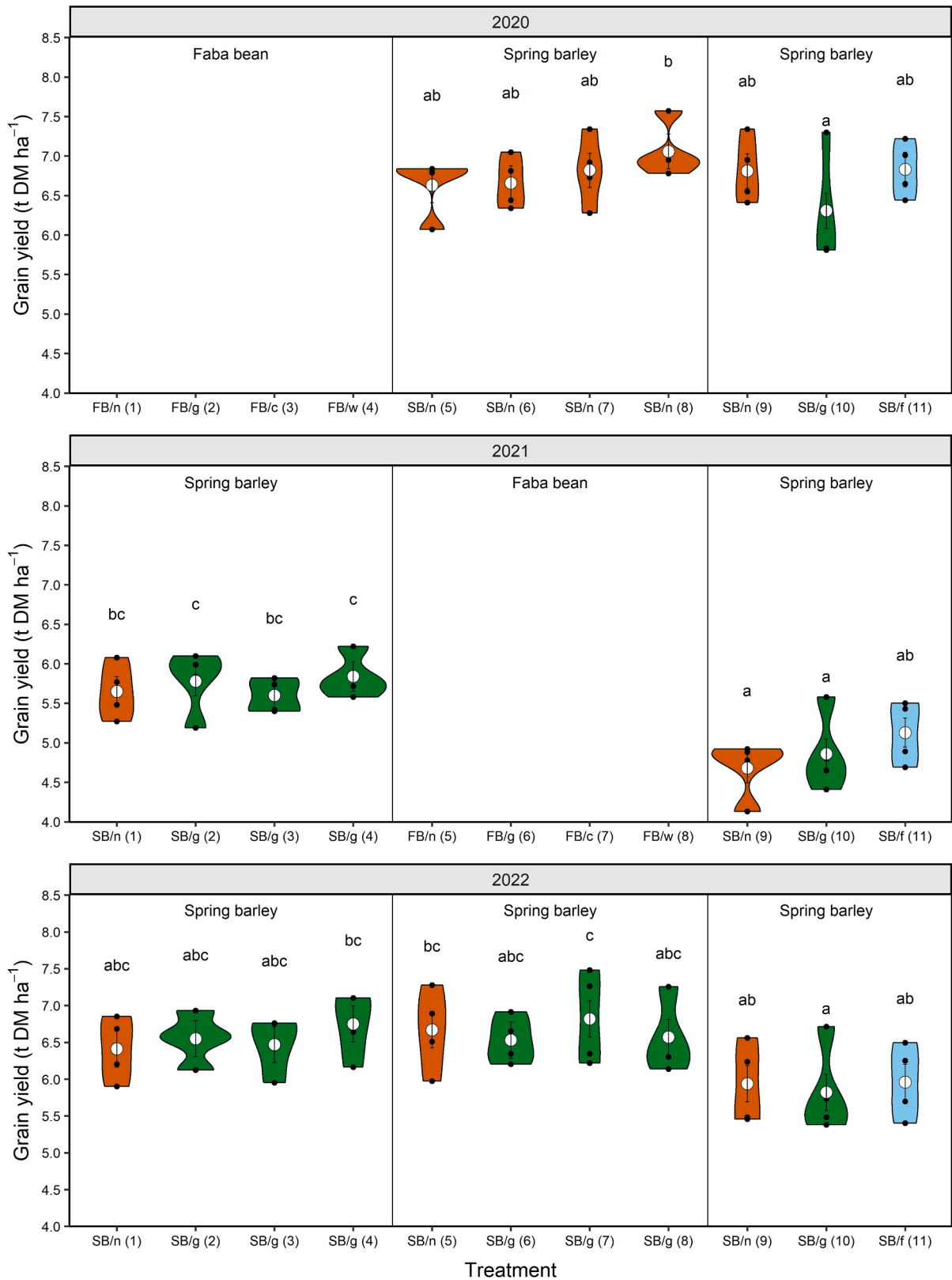


Fig. 2. Grain yield of spring barley (SB) after pre-crop of spring barley or faba bean (FB) with no catch crop (n) or with catch crops of undersown perennial ryegrass (g), post-harvest fodder radish (f), undersown chicory (c), post-harvest winter rye (w). White circles are averages and error bars are standard errors estimated by the statistical models while black circles are measured data from four blocks. Significant differences are presented with different small case letters. Numbers in the brackets are treatment numbers in Table 1. Violin plots show distribution of the measured data with a higher density in a wider region than in a narrow region on the x-axis.

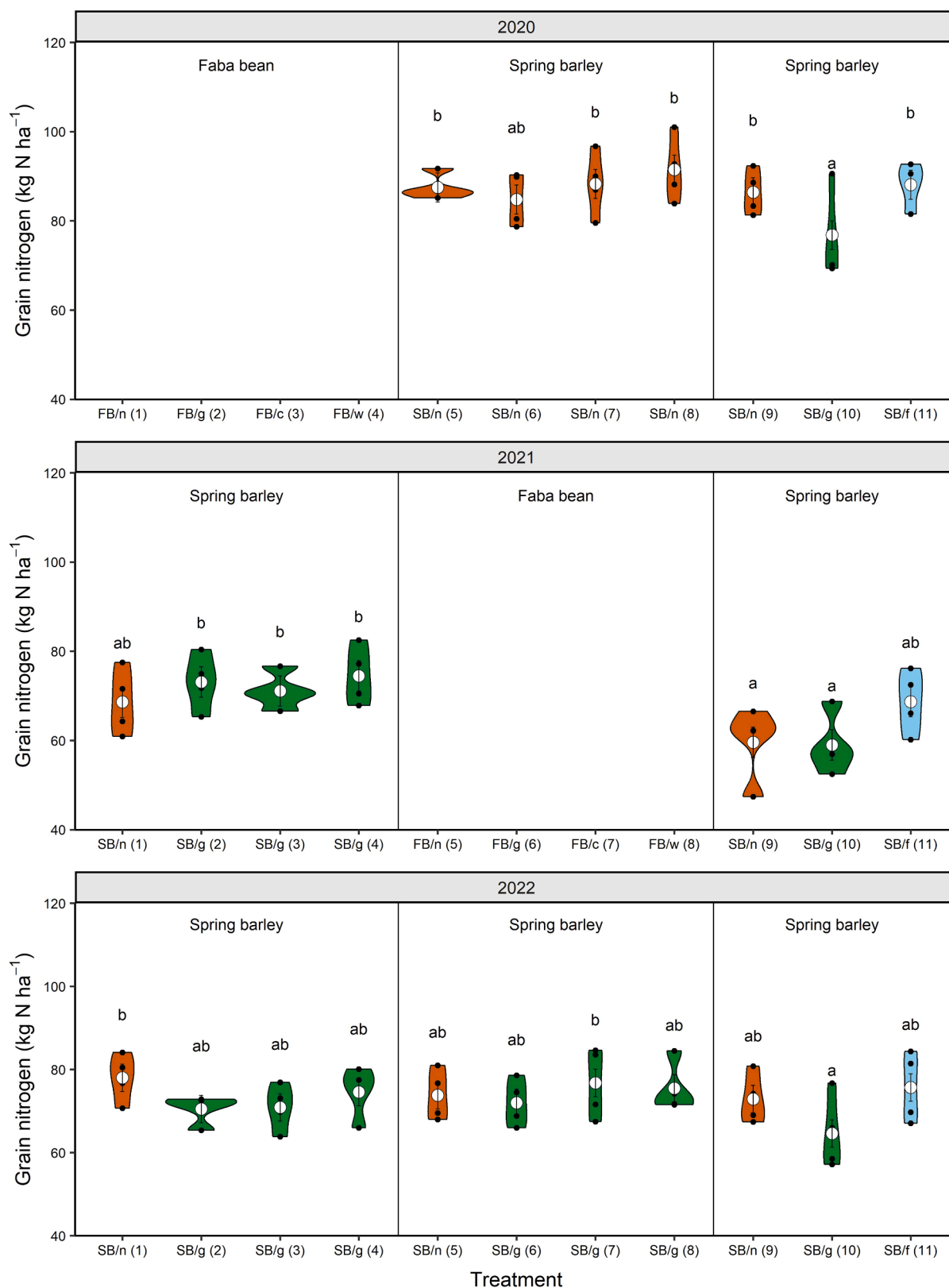


Fig. 3. Grain N in spring barley (SB) after pre-crop of spring barley or faba bean (FB) with no catch crop (n) or with catch crops of undersown perennial ryegrass (g), post-harvest fodder radish (f), undersown chicory (c), post-harvest winter rye (w). White circles are averages and error bars are standard errors estimated by the statistical models while black circles are measured data from four blocks. Significant differences are presented with different small case letters. Numbers in the brackets are treatment numbers in Table 1. Violin plots show distribution of the measured data with a higher density in a wider region than in a narrow region on the x-axis.

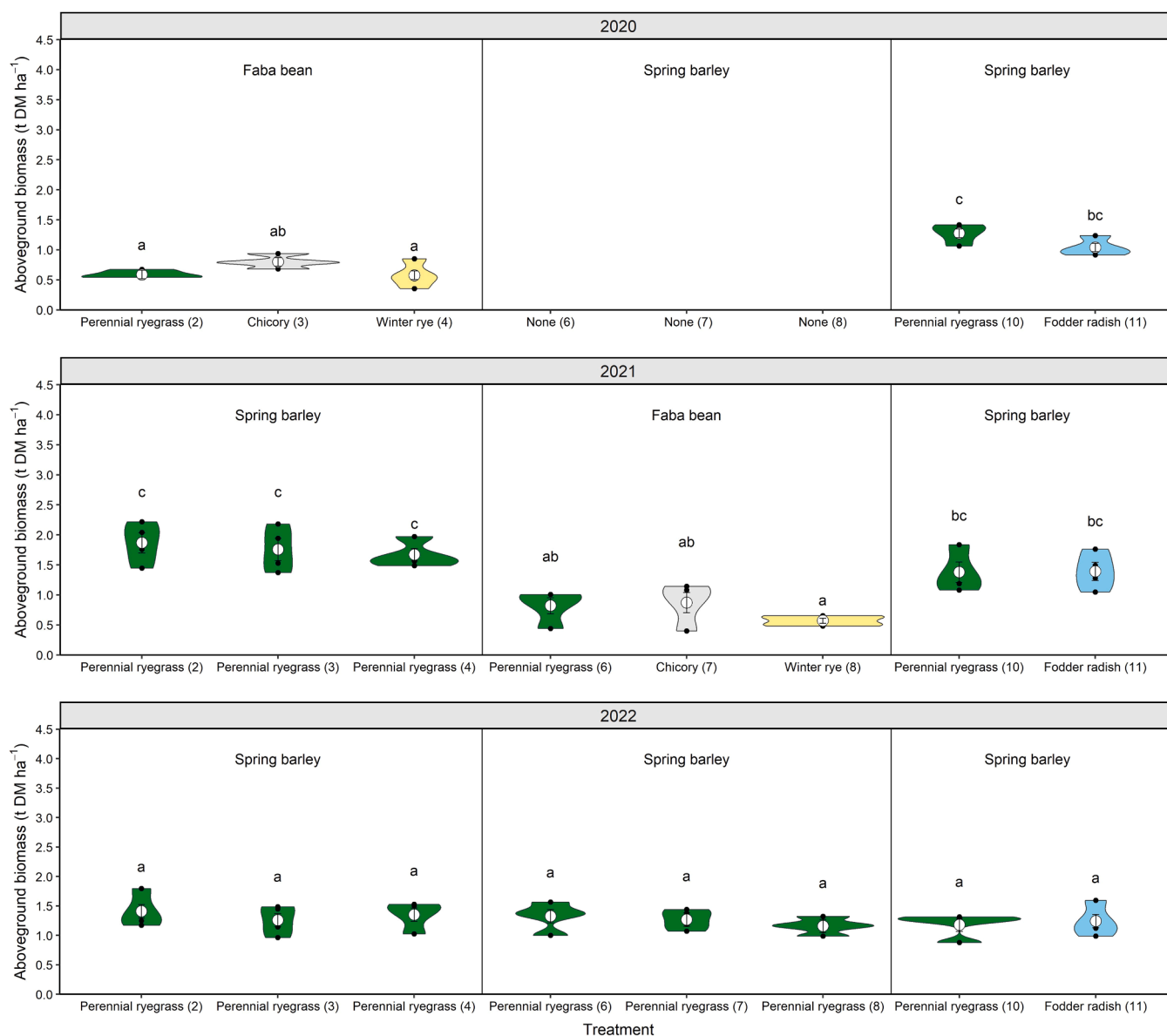


Fig. 4. Aboveground biomass of catch crops grown with the main crop. White circles are averages and error bars are standard errors estimated by the statistical models while black circles represent measured data from four blocks. Significant differences are presented with different small case letters. Perennial ryegrass and chicory were undersown, and winter rye and fodder radish were post-harvest sown.

and weed infestations (Kirkegaard et al., 2008).

4.2. Nitrate leaching: main crop and catch crop combinations

Despite providing a potential source of locally grown protein and many ecosystem services, faba bean cultivation increases the risk of nitrate leaching due to its N-rich residues. Indeed, De Notaris et al., (2023) reported approximately 365 kg N ha^{-1} in the total aboveground biomass of faba bean measured one month prior to harvest and grain N of approximately 220 kg N ha^{-1} at harvest. Maidl et al. (1996) reported that N in the residues of faba bean can be much higher than cereals. In our study, nitrate leaching from both faba bean and spring barley grown without catch crops was not statistically different in the first drainage period in 2020–21. This suggests that the flush-out of nitrate from the mineralization of N-rich residues of faba bean left on the fields after grain harvest was comparable to the nitrate leaching resulting from the leftover mineral N after the spring barley harvest, with the presumption of similar mineralisation of soil organic matter from both systems.

In 2021–22, when both crops were grown without catch crops the nitrate leaching was higher from faba bean than from spring barley. The nitrate leaching from faba bean with catch crops was similar to that from spring barley without catch crops, while that of spring barley with catch crops was significantly lower. This can be explained by accounting three factors: (1) release of N from the mineralization of faba bean residue can lead to similar leaching as from flushing out leftover N after spring barley was harvested (discussed above, and also note that spring barley received fertilization and its residue was removed), (2) significantly lower aboveground biomass and N yield in the catch crops with faba bean than with spring barley could lead to more leaching (De Notaris et al., 2018), (3) and finally higher precipitation particularly from August 2021 to February 2022 (510 mm) in 2021–22 than in 2020–21 (with 400 mm) and hence higher drainage. These three factors together could create conditions for the higher nitrate leaching from faba bean than spring barley observed in 2021–22. The significant reduction of nitrate leaching with catch crops observed in all three drainage periods, is consistent with previous studies with various legume grain crops and

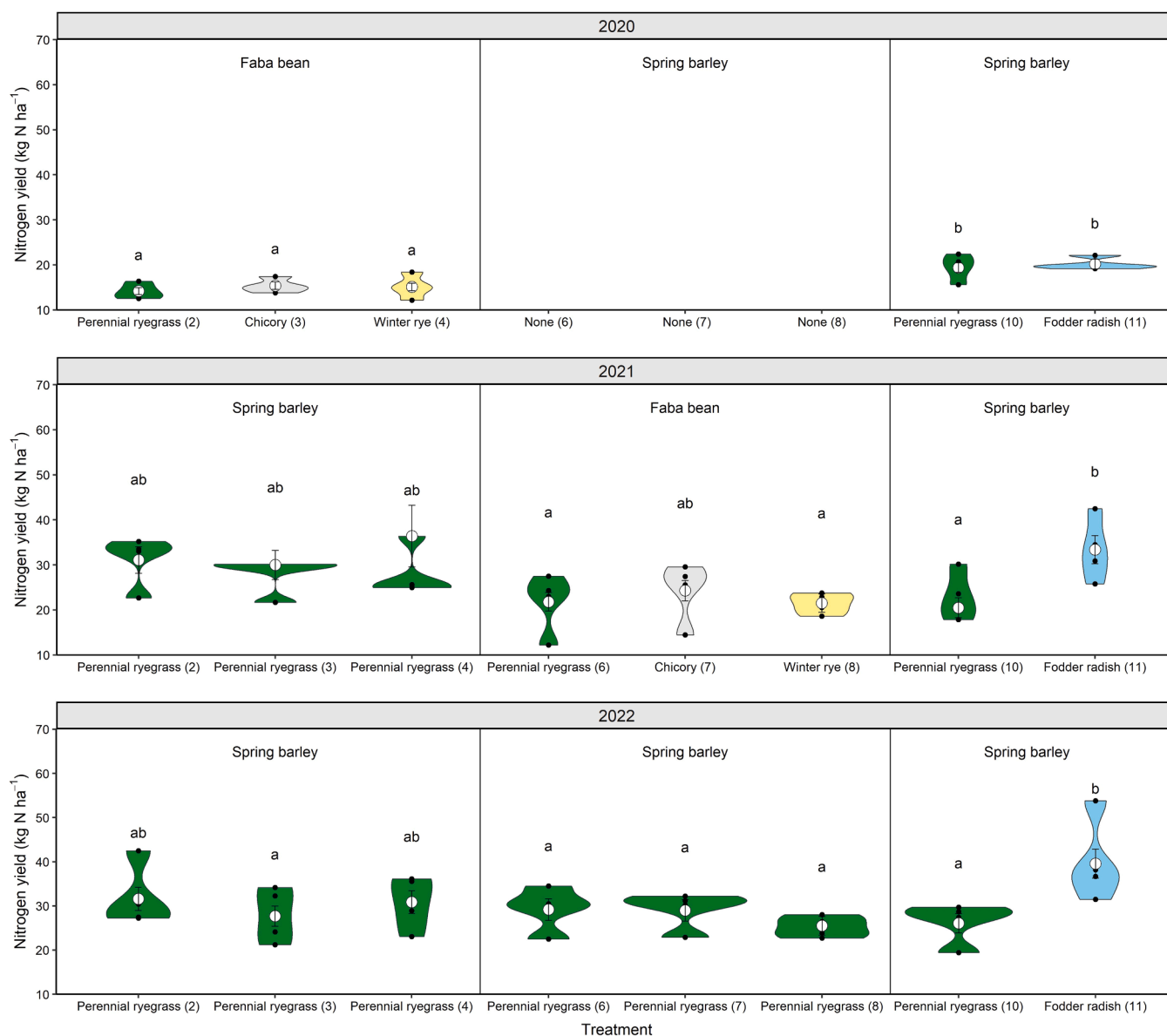


Fig. 5. N yield in catch crops grown with the main crop. White circles are averages and error bars are standard errors estimated by the statistical models while black circles represent measured data from four blocks. Significant differences are presented with different small case letters.

cereal crops (Thomsen et al., 2001; Hauggaard-Nielsen et al., 2009; Böldt et al., 2021; Kumar et al., 2023). In this study, the average reduction of nitrate leaching with main and catch crop combinations in the three drainage periods was 73% (with catch crops: 22 kg NO₃-N ha⁻¹, without catch crops: 80 kg NO₃-N ha⁻¹), which is a little higher than the average reduction of 69% across several main crops and catch crop combinations in a recently published meta-analysis study (Nouri et al., 2022).

The greater contribution of main crop and catch crop combinations ($X^2 = 314$, Table 3) than drainage period ($X^2 = 13$) further suggests the selection of main crop (longer maturity of faba bean than spring barley) and catch crop combinations (type and establishment date and method) are more critical than the drainage period to address the leaching concerns. The use of catch crops in autumn after faba bean is critical (similar to cereal-based systems) to reduce leaching, and this would be even more important when the N rich stubbles of faba bean are left on the field after grain harvest.

5. Conclusion

Grain yield and grain N of faba bean were not affected by undersown catch crops but by years, confirming uncompromised grain yields and grain N of faba bean when catch crops were employed as a tool to reduce nitrate leaching risk. Faba bean, both with and without catch crops increased the grain yield on average by 0.9 t ha⁻¹ and grain N by 7 kg N ha⁻¹ of the following spring barley in 2021 and 2022. Without catch crops, nitrate leaching from faba bean could be similar to spring barley with an average of 64 kg NO₃-N ha⁻¹ and high up to 104 kg NO₃-N ha⁻¹, depending on the growth of catch crops and precipitation in the drainage periods. Aboveground biomass and N yield in catch crops with faba beans were lower compared with spring barley. Different types of catch crops and the undersown and post-harvest establishment methods with faba bean were equally effective in reducing nitrate leaching. During drainage periods with high nitrate leaching, using catch crops with faba bean was not as effective in reducing nitrate leaching as compared to using them with spring barley. Overall, faba bean can be included as a local protein source in cropping sequences in European

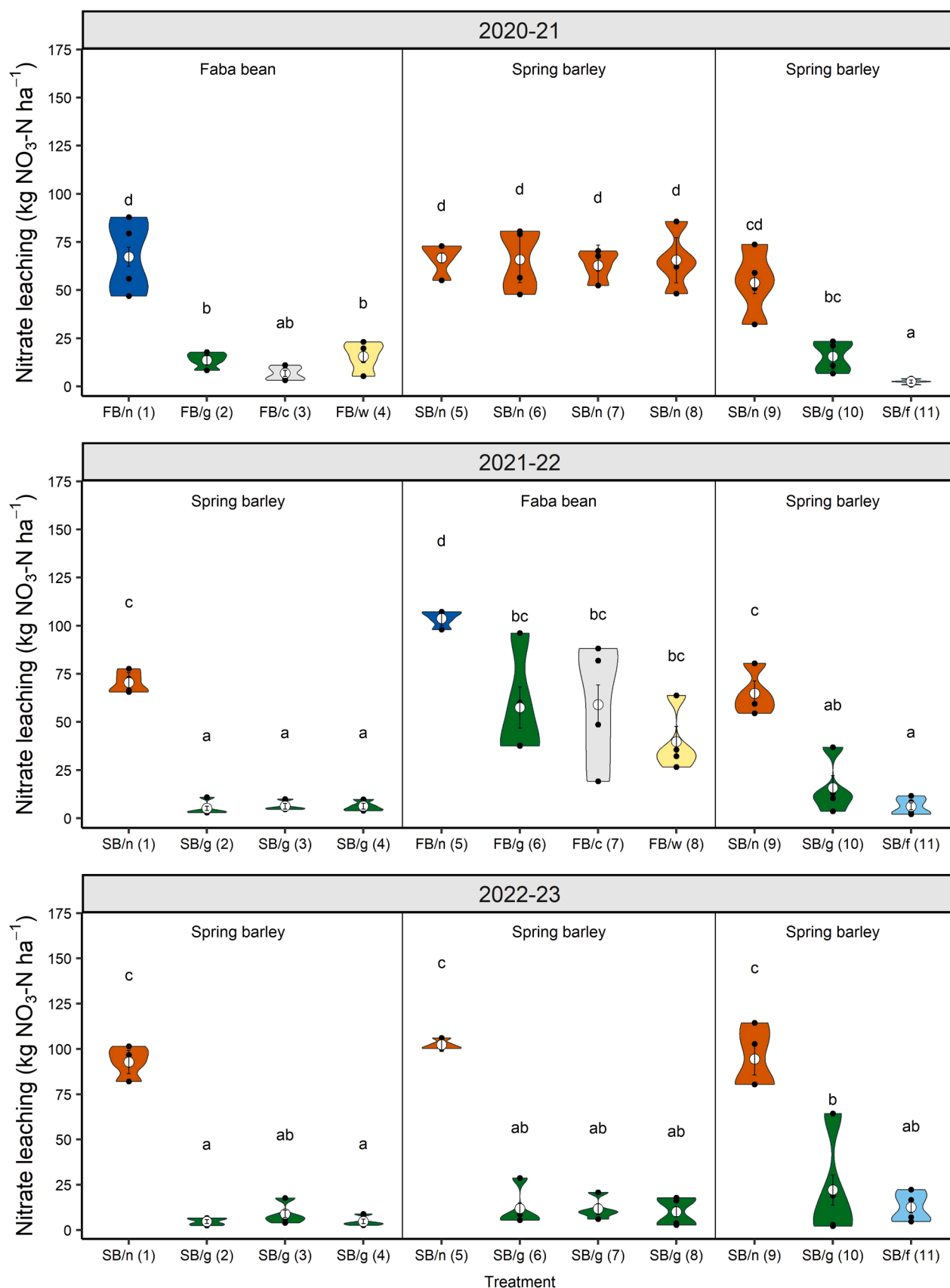


Fig. 6. Nitrate leaching after spring barley (SB) and faba bean (FB) with no catch crop (n) or with catch crops of undersown perennial ryegrass (g), post-harvest sown fodder radish (f), undersown chicory (c), post-harvest sown winter rye (w). White circles are averages and error bars are standard errors estimated by the statistical models while black circles represent measured data from four blocks. Significant differences are presented with different small case letters. Numbers in the brackets are treatment numbers in Table 1.

conditions, which would also foster biodiversity (to break pest and disease cycles) and sustainability (improved soil health and fertility). However, farmers should take into account seasonal variations in precipitation that could particularly affect nitrate leaching, besides grain yield and grain N. Furthermore, understanding the causes of nitrate leaching variability between different drainage periods would be crucial for developing effective strategies to minimize nitrate leaching risks from faba bean.

CRedit authorship contribution statement

Elly Møller Hansen: Conceptualization, Data curation, Project administration, Validation, Writing – review & editing, Methodology. **Uttam Kumar:** Formal analysis, Investigation, Visualization, Writing – original draft, Writing – review & editing. **Maarit Mäenpää:** Formal analysis, Validation, Writing – review & editing. **Ingrid Kaag Thomsen:** Conceptualization, Data curation, Methodology, Project administration, Supervision, Validation, Writing – review & editing. **Jørgen Eriksen:** Conceptualization, Methodology, Validation, Writing – review & editing, Funding acquisition. **Iris Vogeler:** Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

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Declaration of Generative Artificial Intelligence (AI) and AI-Assisted Technologies in the Writing Process

During the preparation of this work the first author used ChatGPT in order to improve writing for better and broader clarity. After using this tool/service, the author reviewed and edited the content as needed and took full responsibility for the content of the publication.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.fcr.2024.109360](https://doi.org/10.1016/j.fcr.2024.109360).

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