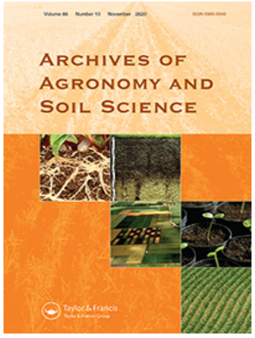


Taylor & Francis
Taylor & Francis Group

Archives of Agronomy and Soil Science

ISSN: 0365-0340 (Print) 1476-3567 (Online) Journal homepage: www.tandfonline.com/journals/gags20

Effect of long-term fertiliser regimes and weather on spring barley yields in sandy soil in North-East Germany

Thi Huyen Thai, Sonoko Dorothea Bellingrath-Kimura, Carsten Hoffmann & Dietmar Barkusky

To cite this article: Thi Huyen Thai, Sonoko Dorothea Bellingrath-Kimura, Carsten Hoffmann & Dietmar Barkusky (2020) Effect of long-term fertiliser regimes and weather on spring barley yields in sandy soil in North-East Germany, Archives of Agronomy and Soil Science, 66:13, 1812-1826, DOI: 10.1080/03650340.2019.1697436

To link to this article: https://doi.org/10.1080/03650340.2019.1697436

ARCHIVES OF AGRONOMY AND SOIL SCIENCE
2020, VOL. 66, NO. 13, 1812–1826
https://doi.org/10.1080/03650340.2019.1697436

Effect of long-term fertiliser regimes and weather on spring barley yields in sandy soil in North-East Germany

Thi Huyen Thai[a,b,c], Sonoko Dorothea Bellingrath-Kimura[a,b], Carsten Hoffmann[a] and Dietmar Barkusky[a]

[a]Land Use and Governance, Leibniz Centre for Agricultural Landscape Research (ZALF), Müncheberg, Germany; [b]Institute of Agriculture and Horticulture, Faculty of Life Science, Humboldt University of Berlin, Berlin, Germany; [c]Faculty of Agronomy, University of Agriculture and Forestry (HUAF), Hue University, Hue, Vietnam

ABSTRACT

The interaction effects of different fertilisation regimes and weather variability on crop yield is a challenge that requires long-term investigation. Therefore, yield data for spring barley (SB) in an agricultural long-term field experiment, established in 1963 in Müncheberg, northeast Germany, were analysed to reveal the effects of 21 fertiliser regimes and different weather conditions on SB yields. SB yields were significantly affected by fertilisation regimes (11%), annual weather conditions (55%) and their interaction effect (8%). Mineral N fertilization decreased overall yield variability across seasons as compared to no fertilization and organic fertilization regimes showed higher yield variability. A suitable combined application of mineral nitrogen and organic fertiliser was found to be an effective way to produce higher SB yields than the application of either mineral nitrogen or organic fertiliser alone. A Bayesian linear regression model showed total precipitation during the growing season (April–July) positively affected on SB yields when high mineral N was supplied. At the early growth stage, a precipitation rate (March) and temperature (April or sowing day) negatively affected on SB yield.

ARTICLE HISTORY
Received 11 May 2019
Accepted 21 November 2019

KEYWORDS
Barley; mineral N fertiliser; organic fertiliser; precipitation; temperature

Introduction

Barley (*Hordeum vulgare* L.) is one of the most important cereals after wheat, maize and rice, grown in more than 100 countries in the world (FAO 2019). Based on statistical evaluations of the Food and Agricultural Organisation (2019), the total production area was approximately 47 million hectares (ha) with a production of approximately 149 million tons (t) of grain at an average yield of 3.2 t ha^{-1} in 2017. In Europe, barley is the second most important cool temperature cereal after wheat. In the last decade, Europe has produced about 60% of global production despite the decline in the production area and grain production (FAO 2019). The major European barley-producing countries are France, Germany, Russia, Ukraine, and Spain. In Germany, the total growing area for barley was approximately 1.6 million ha in 2016, of which the total area for spring barley (SB) cultivation was approximately 340,000 ha (Walter 2017; FAO 2019). Although less area is cultivated for SB than for winter barley, SB is an important crop in the crop rotation and is used not only as animal feed but also for malt production (Friedt and Ordon 2013). In northeastern Germany, SB has a short growth duration of approximately 4 months and is usually sown at the end of March or in early April and harvested at the end of July.

CONTACT Sonoko Dorothea Bellingrath-Kimura belks@zalf.de Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Str. 84, Müncheberg, Germany
Supplemental data for this article can be accessed here.

In general, food security under a globally changing climate requires a comprehensive understanding of fertilisation practices to achieve optimal crop yields while minimising the harmful effects on agroecosystems (Timsina 2018). Fertiliser management is considered an important factor in agricultural production for sustaining crop productivity in agroecosystems (Blanchet et al. 2016). Integrating mineral nitrogen fertiliser with organic fertiliser is a promising management strategy for sustainable agricultural production systems, especially for fields with low soil organic matter contents and dry condition (Yang et al. 2015; Wei et al. 2016; Muller et al. 2017). The effect of integrated organic-mineral fertilisation on SB yield was observed in several studies; the trails, however, show that the strength of the effect may differ depending on soil condition, weather condition in a year, and agronomical factors (Příkopa et al. 2005; Váňová et al. 2006; Černý et al. 2010).

Temperature and precipitation are two major climatic factors that determine crop yields (Peltonen-Sainio et al. 2011). They are important predictors of yield at sensitive crop phenological stages (Peltonen-Sainio et al. 2010; Trnka et al. 2011). Studies by Lobell and Field (2007) found that seasonal temperature and precipitation explained 30% or more of the year-to-year variation in global average yield for the six most commonly grown crops. Other studies in the UK found that 33% of the variation in grain yield and 50% of the variation in straw yield of winter wheat could be explained by precipitation and temperature variation (Chmielewski and Potts 1995). Chmielewski and Köhn (1999) reported that it is possible to explain nearly 60% of grain yield variability in SB and oats with meteorological variables. Thus, detailed observations of weather variables can help to explain yield variabilities for each crop. Furthermore, Freckleton et al. (1999) and Fisher (1925) indicated that there may be significant effects of weather on crop yield and yield variability. However, both studies showed that the directions of these effects were not necessarily consistent, and these effects may interact with nutrient input and the environmental conditions of the study site.

We postulate that using long-term datasets, it is a better way to understand the effects of the two covariates. To obtain effects of fertilizer regimes and weather conditions on SB yields, the data from the 'V140' agricultural long-term field experiment in Müncheberg, northeastern Germany for nine growing seasons over the period from 1976–2016 were analysed. SB was chosen as the sample crop since which shows the highest yield variability and is highly sensitive to weather in spring period (Trnka et al. 2007). We expect that these effects appear more significant at sandy soils with low nutrient inventory and low annual precipitation rates.

Therefore, the objective of this study is to assess the effects of different long-term fertilisation regimes on SB yield under varying annual weather conditions and their interactions. The study addressed the following three research questions: 1) Which weather variables determine SB yield variation? 2) How fertiliser regimes and weather affect SB yield variation? and 3) What different fertiliser management strategies affect SB yield in the long term?

Materials and methods

Site description

The data were collected from the agricultural long-term field experiment (LTFE) 'V140', which was established in 1963 by the German Academy of Agriculture Institute of Agriculture and Crop Production in Müncheberg, Germany (latitude: 52° 30′ N; longitude: 14° 8′ E; altitude: 62 m a.s.l.). The field trial is located approximately 50 km east of Berlin. The soil of the study site is characterised by a high sand content of 740 g kg^{-1} (50 g kg^{-1} clay, 210 g kg^{-1} silt), low total carbon contents (4.3–5.2 g kg^{-1}), a CEC of 31.5–35.6 $mmol_c$ kg^{-1} and a pH_{KCl} of 5.4–5.9 in the plough layer (0–25 cm) (Ellerbrock et al. 1999). The soil type was classified as a Podzoluvisol to Arenosol (FAO 2006). During the experimental from 1963–2016, the mean annual precipitation and average annual air temperature were 540 mm (range: 343–793 mm) and 8.8°C (range: 6.5–10.4°C), respectively.

Table 1. Description of the experimental treatments.

Treatment Code	Group treatment	Organic fertilisation	Mineral N- fertilisation (kg ha^{-1})
0	Control	0	0
1.1			25
1.2	NPK	0	50
1.3			75
1.4			100
1.5	–	0	125
2.1		1.2 t ha^{-1}year^{-1}	25
2.2	NPK+fym1	dry mass farmyard manure	50
2.3			75
2.4			100
2.5	–	1.2 t ha^{-1}year^{-1} dry mass farmyard manure	125
3.1	fym2	3.2 t ha^{-1}year^{-1} dry mass farmyard manure	0
3.2		3.2 t ha^{-1}year^{-1}	25
3.3	NPK+fym2	dry mass farmyard manure	50
3.4			75
3.5			100
4.1		2.0 t ha^{-1}year^{-1}dry mass straw	25
4.2	NPK+Straw		50
4.3			75
4.4			100
4.5	–	2.0 t ha^{-1}year^{-1}dry mass straw	125

Treatments (1.1–4.5) are each rate of mineral N fertiliser (five rates) combined with each organic fertiliser (four variants: no organic, fym1, fym2, straw). Treatment '0': control, no fertilisation. Group treatments: NPK: no organic fertilisation, the average value of N1- N4; NPK + fym1: NPK + 1.2 t DM ha^{-1}a^{-1}farmyard manure; NPK + fym2: NPK + 3.2 t DM ha^{-1}a^{-1}farmyard manure; fym2: only 3.2 t DM ha^{-1}a^{-1}farmyard manure; NPK + straw: NPK + 2 t ha^{-1}a^{-1}straw.

Experimental design

The experiment followed a randomised complete block design with 21 treatments (including a control, Table 1), each with eight replicates. The plot size was 30 m^2 (6.0 m × 5.0 m). The cropping system was conventional tillage with ploughing in autumn or in the spring depending on the date of harvesting of preceding crop and weather conditions in autumn. The seedbed was prepared immediately before sowing. Different crops (winter wheat, winter rye, spring barley, potato, sugar beet, pea, maize, and oil flax) were annually cultivated in a cropping system (Supplementary Table S1). The present study focused on dry mass grain yield data of nine SB growing seasons in 'V140' from 1976–2016. Because of lack of the eight replication of the treatment in the first 9 years (1963–1971). Since 1972, SB started to cultivate in crop rotation since 1976.

Spring barley was sown from the end of March to early or mid-April (mean daily air temperature mostly > 5.0°C) and was commonly harvested between the end of July to the beginning of August depending on weather conditions. The experimental period was separated into two distinct periods: (1) six SB seasons from 1976 to the period before 2000, where farmyard manure (fym) was applied every 2 years to sugar beet fields (preceding crop), and (2) three SB seasons from 2000 to 2016, where fym was amended every 4 years to potato fields (preceding crop). The separation is necessary due to changes in crop rotations and change time for applying manure in 1999. Sugar beet used in a rotation of period 1 in 1975, 1977, 1979, 1981, 1985 and 1989. Potato served as the preceding crop in rotation of period 2 in 1999, 2007, 2015. The average nutrient contents of dry mass manure used in the experiment were 2.3% N, 0.9% P_2O_5, 2.3% K_2O, 1.6% Mg and 55.9% organic matter. Straw was applied every 2 years throughout both periods (using the straw from the harvested cereal). Average nutrient contents of dry mass straw used in the experiment were 0.6% N, 0.1% P_2O_5, 1.5% K_2O and 0.08% Mg. The ploughing, cultivation, sowing, and liming methods and seeding rate were the same for all plots. The phosphorus and potassium fertilisation rates (50 kg ha^{-1} P_2O_5 a^{-1}, 150 kg ha^{-1} K_2O a^{-1}) were the same for all plots (In control plot phosphorus and potassium fertiliser were applied only in the years 1978 and 1980). Mineral nitrogen fertiliser was annually applied two twice during SB growth, after seeding (the end of March or early or mid-April) and between shooting to full bloom (the end of May or early June). Mean values of soil chemical analyses of each treatment through eight growing years of SB (except 2000 lack of data) are shown in the Supplementary Table S2. Soil influence on SB yield could study in another paper. The used varieties of SB changed over time: "Trumpf" variety was used in 2 years (1976 and 1978), different varieties were cultivated between 1980 and 2000, and "Simba" variety was used in both years 2008 and 2016. Weeds were controlled with a postemergence herbicide. SB was harvested at the time of technological maturity by plot harvester.

Description of the treatments

Five different rates of mineral nitrogen fertilisation (MN) were applied with four organic fertiliser (OR) regimes: i) no OR, ii) 1.2 t dry mass (DM) ha^{-1} a^{-1} farmyard manure (= fym1), iii) 3.2 t DM ha^{-1} a^{-1} farmyard manure (= fym2), and iv) 2.0 t DM ha^{-1} a^{-1} straw (Table 1). In addition to the control (no fertilisation), the five MN rates were 25, 50, 75, 100, and 125 kg ha^{-1} N, which are referred to as N0, N1, N2, N3, N4, and N5, respectively. In the regime with no OR, fym1 and straw, the N1, N2, N3, N4 and N5 rates were included, while in the fym2 regime, N0, N1, N2, N3, and N4 were included, respectively. Together with the control treatment, 21 treatments were included in this experiment. Treatments were grouped as shown in Table 1. The straw from each crop was removed from the experimental plots after harvest.

Meteorological and crop data

Dry mass grain yield data of SB obtained from every plot in 9 years of SB cultivation from "V140" from 1976 to 2016 was used for analysis in this study. Due to the irrigation conducted in 1976, 1978 and 1980, only four replicates without irrigation were evaluated for these years.

Meteorological data used in the analysis were obtained from an adjacent climate station of the German Meteorological Service (DWD station number 03376 via the link opendata.dwd.de/climate_environment/CDC/observations_germany/climate/daily/kl/historical). For every year of SB cultivation, averages daily air temperature and sum daily precipitation were used to calculate the average monthly temperature, monthly precipitation during the growing season, and average temperature and total precipitation during the whole growing season (April–July) to estimate weather effects on yield and yield variability. Additionally, total precipitation from the prior winter (October–February) was used in statistical analyses.

All corresponding agricultural data of the V140 experiment, including the yield, fertiliser, plant and soil laboratory data, are open access and can be downloaded from the BonaRes Data Portal (BonaRes 2019), excluding the data from the last ten years.

Statistical analysis

Analysis of variance (ANOVA) was used to estimate SB yield variation due to the effects of treatment or year (annual weather conditions) and interaction effects between year and treatment by using a general linear model. In the case of a significant ANOVA result, Tukey's HSD post hoc test was used to assess the differences in mean yields among treatments every year and over the years. The treatment effects were declared significant at $P < 0.05$. When the SB yield data were evaluated over the years, fertiliser applications were included as fixed factors and SB planting year were included as random factors in the model. The ANOVA took into consideration the randomised complete block design of the experiment.

A multiple linear regression model (MRM) was used to evaluate the SB yield data as a function of weather parameters. To avoid the effects of collinearity, a correlation analysis of weather variables was conducted to choose the appropriate variables to be included in the MRM. Temperature and precipitation were tested using linear regression analysis, with a Pearson correlation matrix as the starting point. The proportion of significant results obtained from the matrix indicated whether a particular variable should be included in the MRM. The tested factors were considered to be statistically significant at $P < 0.05$. We used the Bayesian method for the MRM by Bayesian model averaging (BMA), following (Raftery 1995; Raftery et al. 1997; Hoeting et al. 1999). The model for yield response (y_i: dependent variable) to k weather variables (x_{1i}, x_{2i}.. x_{ki}: independent variables) has the following form (Gomez and Gomez 1983):

$$y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \ldots + \beta_k x_{ki} + \varepsilon_i \tag{1}$$

where i is the ith data point (i = 1, …, n), y_i is the yield of SB in particular treatments over 9 years, β_0 is the intercept term, other weights, i.e., β_1, β_2, …, and β_k, are regression coefficients (k slope) of the k weather variables (x_{1i}, x_{2i}, …, x_{ki}), respectively, and ε_i is the error term, i.e., the residual of point i from the fitted surface. BMA usually displays the five best models found, but in this study, we report the first model since it is usually the best. The BMA is the model that includes all explanatory variables whose posterior probability (P! = 0) is greater than 50%. 'P! = 0' is the posterior probability that the regression coefficient of each variable is non-zero (in %). The BIC (Bayesian information criterion) 'is a criterion for model selection among a finite set of models; the model with the lowest BIC is preferred'. We performed all statistical analyses in SPSS version 22, R version 3.4.4 and Excel 2013.

Results

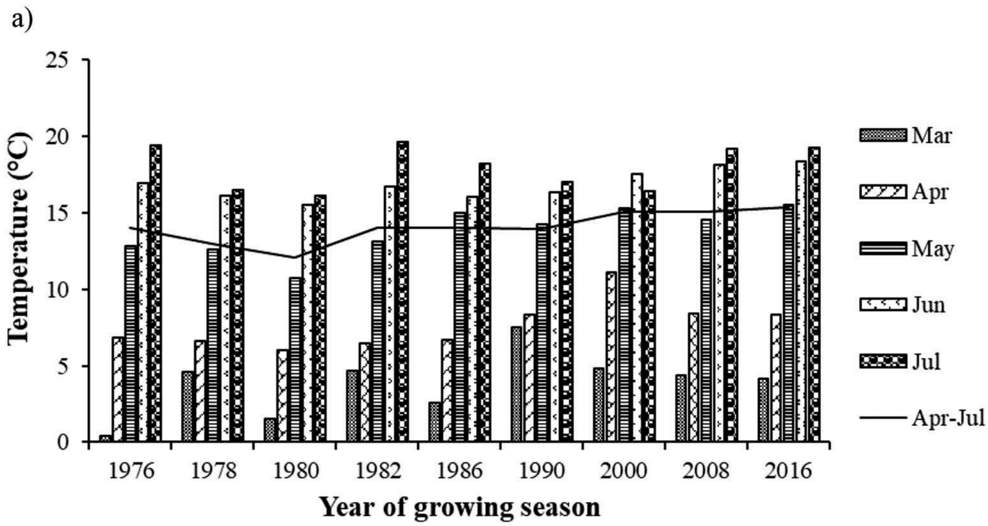
Temperature and precipitation during the spring barley seasons

The lowest average monthly March temperature was 0.4°C, in 1976, while in 1990, it was highest, at 7.5°C (Figure 1(a)). The highest monthly average temperature was in July 1982, at 19.6°C. The average SB growing season temperature increased by approximately 1.4°C between 1976 and 2016. The total precipitation in each SB growing season was between 82 and 271 mm (Figure 1(b)). In six of the 9 years (1976, 1978, 1982, 2000, 2008, and 2016), the largest amount of precipitation during the growing season was less than 170 mm. In most growing seasons, the month with the lowest precipitation was May. This was especially the case in 2008 when the amount of precipitation was 4.3 mm in May. The wettest month was June in most growing seasons. In June 1990, the highest amount of precipitation was recorded (165 mm).

Effect of temperature and precipitation on spring barley yield

SB yield was significantly negatively correlated with the average temperature in April in 16 of the 21 treatments; air temperature on the sowing day in 10 of the 21 treatments; temperature on the harvest day in three of the 21 treatments; average temperatures in May, July and the growing season (April–July) in one of the 21 treatments (Figure 2(a)); and the amount of precipitation in March in 15 of the 21 treatments (Figure 2(b)). The yield was significantly positively correlated with the amount of precipitation in June in one of the 21 treatments and total precipitation from April to July in seven of the 21 treatments.

The results from the multiple regression analysis by BMA presented in Table 2 revealed significant negative effects of the average temperature in April and sowing day temperature on SB yield. The effects were explained in 12 treatments, with β_1 values ranging from 0.101



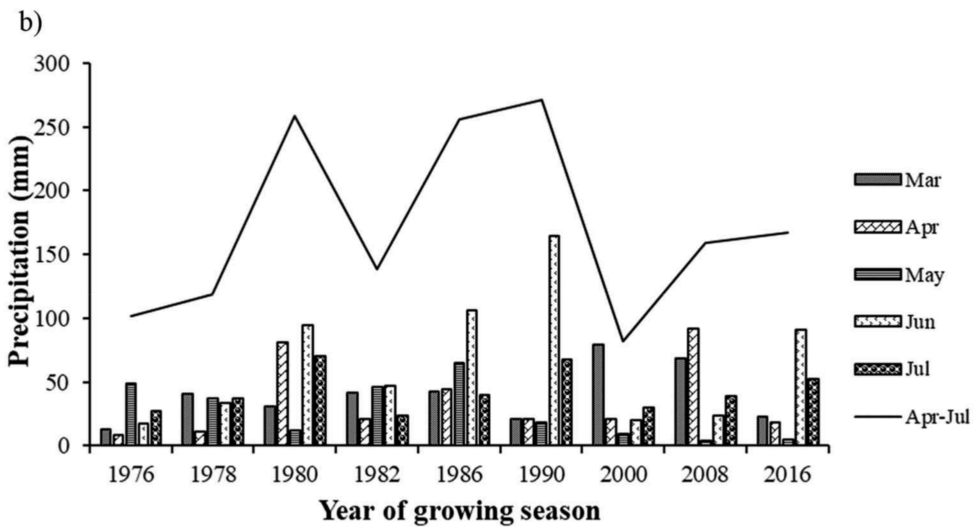


Figure 1. a) Average monthly temperature and b) total monthly precipitation during spring barley growing season in the long-term experiment.

The bars show the average temperature and sum of precipitation for each month (March to July) just before sowing and during spring barley growing season; the solid line shows an average of temperature and the total amount of precipitation during the growing season (April–July).

to 5.639, for the temperature in April and in 16 treatments, with β_2 values ranging from 0.053 to 1.265, for sowing day temperature. Regarding precipitation, there were negative effects of the amount of precipitation in March on yield but positive effects of the total amount of precipitation from April–July on yield. The negative effects of the precipitation in March on yield was explained in 19 treatments, with β_3 values ranging from 0.010 to 1.806. The positive effects of the precipitation from April–July on yield were explained in 12 treatments except treatments low MN (treatment 1.1, 1.2, 2.1, 2.2, 3.1–3.3, 4.1, 4.2), with β_4 values ranging from 0.004 to 7.194. Based on R-squared values, the weather variable effects explained 65-99% of the variation in yield among the treatments. The coefficients of variation (Cv_s) in SB yield among the different fertiliser treatments ranged from 0.35 to 0.50.

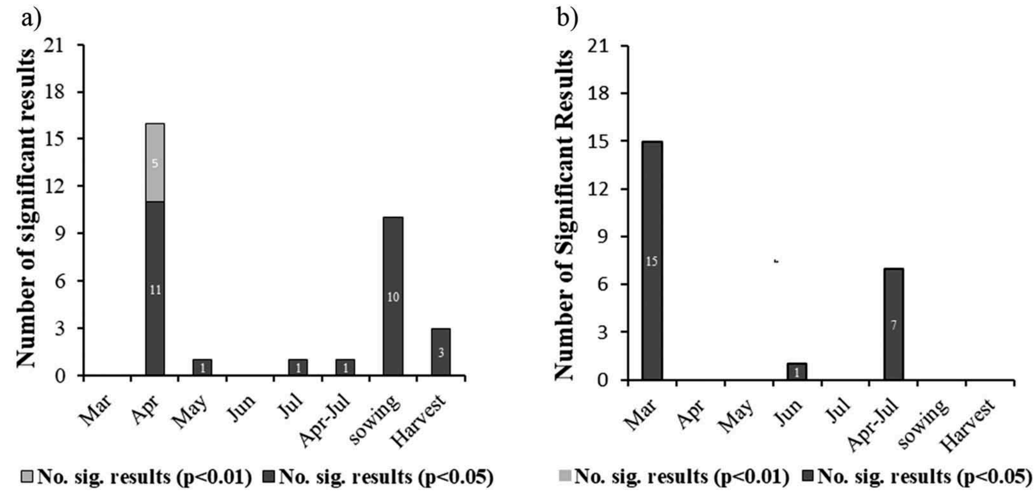


Figure 2. Number of significant results ($P < 0.05$, $P < 0.01$) obtained from linear regressions of 21 mean yields from each treatment on a) average monthly temperature and b) total monthly precipitation.

Table 2. Summary of means, variation coefficients in yields and the results of multiple regression models of yields on weather variables.

	Yield (Mg DM ha^{-1})											
Treatment	Mean	CV	Intercept (β_0)	β_1	P! = 0 (%)	β_2	P! = 0 (%)	β_3	P! = 0 (%)	β_4	P! = 0 (%)	R square
0	1.17	0.46	3.104	–	–	−0.073	61.8	−0.016	68.8	−0.004	60.9	0.685
1.1	2.16	0.37	5.047	−0.314	92.0	–	–	− 0.012	57.8	–	–	0.752
1.2	2.56	0.37	5.928	−0.264	90.4	−0.089	80.8	−0.015	71.7	–	–	0.871
1.3	2.80	0.40	5.293	−0.260	80.8	−0.076	62.8	−0.016	64.7	0.004	67.0	0.866
1.4	2.80	0.38	4.116	−0.149	76.7	−0.099	100	−0.013	91.7	0.007	100	0.957
1.5	2.80	0.40	3.782	–	–	−0.116	100	−0.026	100	0.006	96.3	0.923
2.1	2.29	0.36	3.918	–	–	−0.103	67.5	−0.019	58.9	–	–	0.647
2.2	2.91	0.36	6.611	−0.291	90.3	−0.086	73.7	−0.019	78.1	–	–	0.872
2.3	2.86	0.38	4.314	–	–	−0.123	98.1	−0.027	98.1	0.004	63.5	0.886
2.4	2.92	0.39	3.798	–	–	−0.145	100	−0.020	100	0.006	100	0.946
2.5	3.29	0.38	5.600	−0.383	81.6	–	–	−0.018	65.1	0.006	57.6	0.800
3.1	2.26	0.50	5.778	−0.500	58.2	–	–	–	–	–	–	0.409
3.2	3.01	0.43	7.126	−0.393	67.6	–	–	−0.028	80.3	–	–	0.712
3.3	3.13	0.38	5.683	–	–	−0.161	90.7	−0.030	89.0	–	–	0.795
3.4	3.09	0.38	4.434	–	–	−0.135	97.6	−0.026	97.4	0.005	71.6	0.877
3.5	3.07	0.37	4.148	–	–	−0.122	93.8	−0.024	95.5	0.005	81.5	0.876
4.1	2.62	0.39	6.927	−5.639	100	–	–	–	–	–	–	0.765
4.2	2.57	0.38	5.802	−0.242	75.3	−0.096	67.2	−0.015	56.5	–	–	0.782
4.3	3.11	0.35	5.448	−0.330	100	−0.053	56.6	−0.010	51.9	0.006	100	0.933
4.4	3.00	0.37	4.738	−0.101		−0.111	83.7	−0.023	100	0.005	100	0.986
4.5	2.74	0.40	3.269	–	–	−1.265	100	−1.806	100	7.194	100	0.977

The mean (Mg dry mass ha^{-1}), the coefficient of variation in yields for each treatment over the years. The weights β_1, β_2, β_3, and β_4 are regression coefficients (slopes) of weather variables: April temperature (x_1), temperature of sowing day (x_2), March precipitation (x_3), precipitation from April–Jul (x_4), respectively. P! = 0 is the posterior probability that each variable is non-zero (in percent), P! = 0 in model select >50%. R^{-1} values for the models.

Spring barley yield

Spring barley yield under different fertiliser regimes and weather conditions

The lowest yields were observed in the control treatments ($P < 0.05$) (Figure 3) for all years except 2008, where the yield was not significantly different from the yield in fym2. The highest yields were

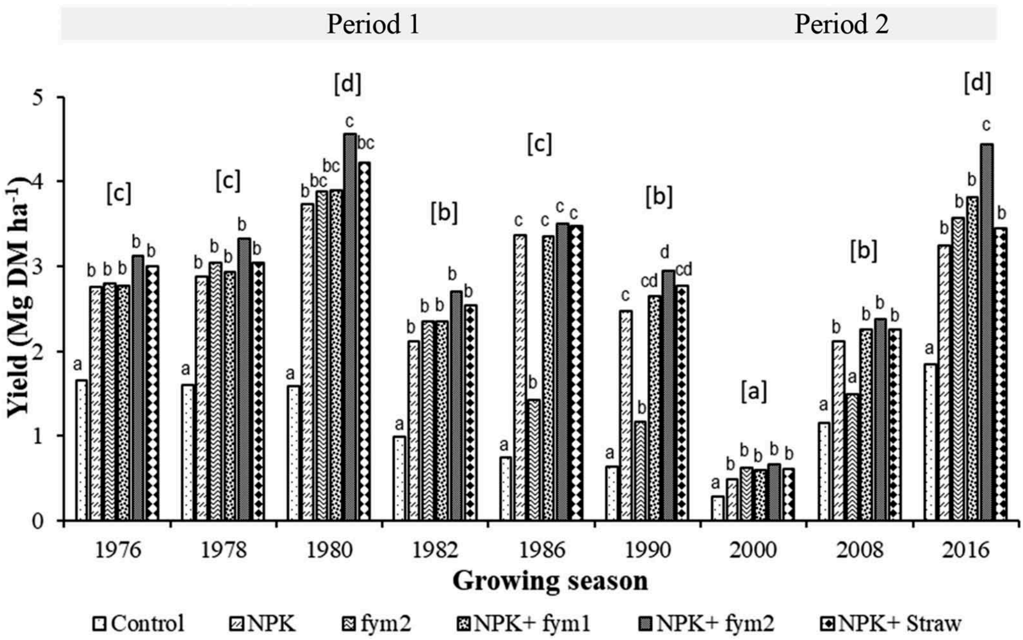


Figure 3. Effect of fertiliser applications (group treatments) on the spring barley yield (Mg dry mass ha^{-1}) every year.

Significant difference mean spring barley yield by group treatments or by average all treatments (include control) in a certain year by Tukey Test. Means sharing the same letters are not significantly different (P < 0.05). Letters in square brackets at the top of bars compare the mean SB yield of all treatments between different years. Letters at the top (without square brackets) of bars compare mean SB yield of group treatments within a year. Treatment groups are given in Table 1.

Table 3. Averaged yield and variation of spring barley yields between group treatments based on the level of mineral nitrogen and organic fertiliser application in the long-term experiment through the seasons.

Group treatment	Yield (Mg DM ha^{-1})	±Se	CV	Yield increase compare to control (%)	Yield increase compare to NPK (%)	Yield increase compare to fym2 (%)
Control	1.17^{a}	0.18	0.46	–	−55	– 48
NPK	2.58^{c}	0.32	0.37	121	–	14
fym2	2.26^{b}	0.38	0.50	93	−12	-
NPK+ fym1	2.74^{c}	0.33	0.36	134	6	21
NPK + fym2	3.08^{d}	0.39	0.38	163	19	36
NPK + straw	2.83^{c}	0.34	0.36	142	10	25

Group treatments are given in Table 1. Mg DM: Mega gram dry mass; Se: standard error; CV: coefficient of variation. Different letters in the same column present that the difference was significant at P < 0.05.

observed in 1980 and 2016, and the lowest yields were observed in 2000. The yields in 1976, 1978, and 1986 were not significantly different. Additionally, the yields in 1982, 1990, and 2008 were not significantly different (P < 0.05). There was no significant difference in SB yield among the different fertiliser treatments in most crop years. In 1980, 1990, and 2016 the yields in NPK+fym2 were significantly higher than those of all other fertiliser treatments.

The effects of fertiliser management on SB yield in the long term

The average SB yield in the most productive treatment (NPK+fym2) was approximately 3.1 t ha^{-1} a^{-1} (Table 3). The average yield in the control treatment was 1.2 t ha^{-1} a^{-1}, which was approximately 61% lower than that in the most productive treatment. The effect of the combined application of MN and OR (NPK+fym1, NPK+fym2 or NPK+straw) on SB yield was significantly greater than that of OR only (fym2), but only the combination of NPK+fym2 had a significantly different effect on SB yield than the treatment with MN only (NPK). The size of the positive effect of the combined application ranged

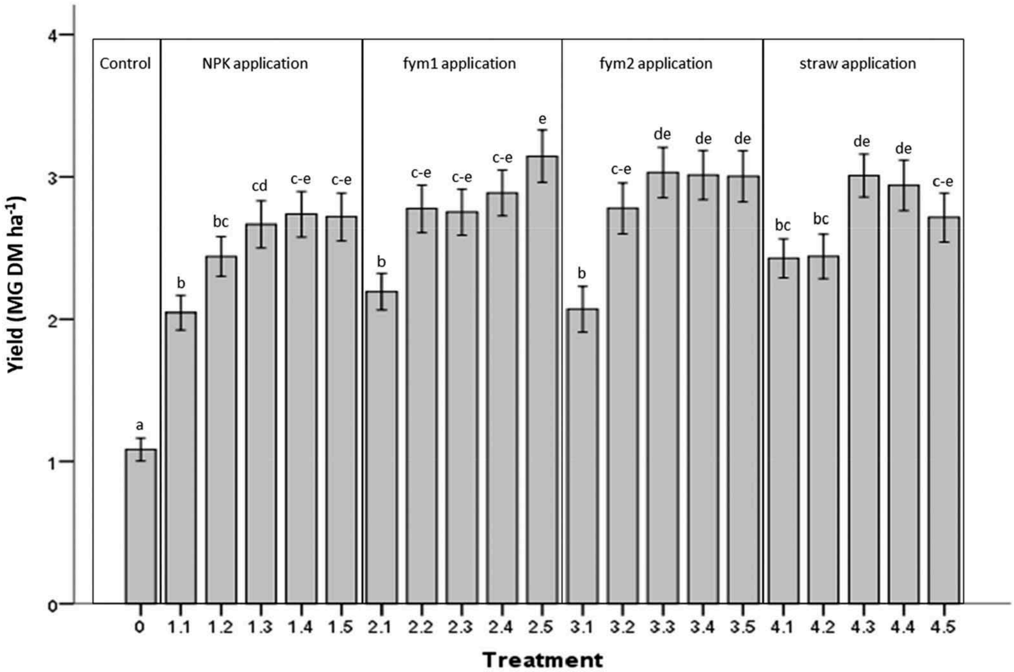


Figure 4. Effect of fertilisers on spring barley yields through nine growing seasons in every treatment.

Vertical lines indicate standard error (SE). A significant difference in spring barley by individual treatments over the year by Tukey Test. Treatments sharing the same letter are not significantly different ($P < 0.05$). Treatment numbers are given in Table 1.

between 134% and 163% compared to the control treatment, while fym2 and NPK increased SB yield by 93% and 121% compared to the control treatment, respectively. The combined application increased the SB yield by 21-36% compared to the fym2 treatment and by 6-19% compared to the NPK treatment. The coefficients of variation (Cv_s) in SB yield among the different combinations of fertiliser application and NPK application were a lower value than those in the control and fym2.

Under all four fertilisation applications (NPK, fym1, fym2, and straw), SB yield was significantly higher than that in the control treatment (Figure 4). The application of fym2 had a significant effect on SB yield at the low MN supply rates of 25–50 kg N ha^{-1}. While the application of fym1 and application of straw did not have a significant effect on yield at low MN supply rates of 25–50 kg N ha^{-1}. The highest SB yields of this study were obtained when 50 kg ha^{-1} MN was applied with NPK, fym1 or 75 kg ha^{-1} N was applied with straw or 25 kg ha^{-1} N was applied with fym2. The result of ANOVA (sum of squares, type III) showed that barley yield variability was significantly ($P < 0.05$) affected by year, representing annual weather conditions (55%), followed by treatment, representing fertiliser application (11%), and the year × treatment interaction (8%); 26% of the variation was due to error (other factors), and the adjusted R-squared was 0.703 (Supplementary Table S3).

The SB yields in the fertiliser treatment fluctuated in the first seasons (1976, 1978, 1980, 1982, 1986), a steady decline in 1990 and dropped sharply in the year 2000 (in period (1)), when the yield increased rapidly for two consecutive seasons. The variability was similar in the control at a lower level, but with a much smoother gradual went down and reached the bottom in 2000, later increases quickly in SB yield (Figure 3, Supplementary Figure S1). Among other factors, the preceding crop could also have an effect on SB yields. In this experiment, the preceding crop used in rotation for the seasons before 2000 was sugar beet, while from 2000 to later seasons, potato was used as the preceding crop.

Discussion

Yield response to weather at the early growth stage

The weather conditions during the early growing stages are key determinants of the germination and emergence of a crop, which determine the crop yield (Zhou et al. 2007; Peltonen-Sainio et al. 2010; Hakala et al. 2012). This relationship was confirmed by the findings from this study: the SB yields were negatively affected by the average temperature in April, the temperature on the sowing day and the precipitation rates in March (Figure 2(a b), and Table 2). This finding reflects an old Finnish saying referenced in the study of Hakala et al. (2012): 'shivering sets the seed,' implying that cold weather at the beginning of plant growth assures better yields in a temperate climate. Our result indicates that low temperatures at the early stage of plant growth (April) have beneficial effects on yield, as slow growth of the aboveground plant parts makes the plant tolerant to cold weather. Therefore, stem and leaf development is delayed, and roots may reach deeper into the soil, which helps the plant acquire more nutrients and water. In contrast, high temperatures may hasten growth, shorten developmental stages, especially the grain-filling period, and reduce yield (Evans 1976; Peltonen-Sainio et al. 2011). Moreover, higher temperatures also lead to higher evapotranspiration and subsequently increased soil water losses, resulting in drought, which can lower the yield capacity and result in a lower yield (Rajala et al. 2011; Peltonen-Sainio et al. 2015). Similar findings were reported by Peltonen-Sainio et al. (2011), who demonstrated negative yield responses to high temperature during early and mid-developmental stages. The results of this study are in accordance with results from Chmielewski and Köhn (1999), which showed that the yields of barley and oats in Germany decreased when the temperatures during the early growth stage were higher than the average temperature.

Regarding precipitation, it showed that high precipitation in March (before the growing season) led to a decrease in yield. Leaching may reduce nutrient availability and restrain seedling emergence and causing lower suboptimal density, which leads to lower yields. This is, especially then the case, when the period before sowing (March) is unusually wet or even affected by heavy rainfall and the period after sowing (April) is dry and warm (Zhou et al. 2007). Additionally, a large amount of pre-sowing precipitation can delay spring sowing due to soil saturation (Trnka et al. 2011), leading to a decrease in yield. Peltonen-Sainio et al. 2015) also found that delayed sowing is a cause of reduced yield when the conditions after sowing are too hot and dry for optimal yield formation. This explanation is shown explicitly in 2000, when high precipitation in March (80 mm) was followed by very late sowing (April 19th), a dry period after sowing which together and end up in low yields in summer. In contrast, in years of early sowing days (April 4th, 24 March 1980th, 2016) SB yields were above average (Figure 3). As high precipitation in March and high temperature during the early growing season have a strong effect on later growth.

Yield response to nutrients and weather

The interaction effect of annual weather conditions and fertiliser application on the variation in SB yield from year to year was pronounced. The lowest yield of SB was in the year 2000, which had high drought stress in the growing season after wet conditions in March (Figure 3). The average temperature and total precipitation in the growing season (April–July) in 2000 were 15.1°C and 82 mm, respectively. Consistent with other findings (Fernandez-Getino et al. 2015), our data showed that the average SB yield in the best fertiliser treatment (NPK+fym2) was significantly different from that in some other treatments in the years (1980 and 1990) with greater precipitation during the growing season. These findings can be attributed to the effect of fertilisation on the crops under sufficient water and drought conditions (Freckleton et al. 1999). The findings are further confirmed by the results of the MRM of SB yield and weather variables presented in Table 2, which showed that the yield in the NPK+fym2 treatment varied due to the sowing day temperature and March precipitation, which are important water availability factors for crops in the initial stages. The results of the model indicated the importance of favourable weather conditions for the growth of SB, as they later led to an increase in yield. Considerably lower yields were obtained in dry years (1982, 2000, and 2008, with total growing season precipitation <160 mm) as a consequence of hot temperatures and dry conditions. The SB in the fertiliser treatments did not perform well since the crop is very sensitive to heat and water deficits, especially during tillering (Svobodová and Misa 2004; Pohanková et al. 2018).

In the period (1), the barley yields obtained in 1976 and 1978 were not significantly different when the same variety ('Trumpf') was used (Figure 3). The average temperature and total precipitation in the growth period in 1976 and 1978 were similar, with averages of 13.9°C and 12.9°C and 102 mm and 119 mm, respectively (Figure 1(a, b)). However, in period (2), the yields obtained in 2008 and 2016 were significantly different when using the same variety ('Simba'). The average temperature and total precipitation in the growth period 2008 and 2016 were similar, with averages of 15.1°C and 15.4°C and 159 mm and 167 mm, respectively. However, precipitation rates were highest in March and April in 2008 but decreased in the later stages (May–July). In 2016, in contrast, there was less precipitation in the early growth stage from March to May and higher precipitation from June to July, particularly in June. This may have caused the lower SB yield in 2008 than in 2016.

The coefficients of variation indicated that increasing the level of nutrients applied to SB decreased the degree to which the yield responded to the climate in general, with the exception of fym2. This is consistent with findings from Macholdt et al. (2019) and Ellmer et al. (2001), who noted that a stable supply of nutrients to crops could improve not only their grain yield but also their yield stability. The chemical fertilisation treatment improved the nutrient availability more than the control and organic material application alone. The fym2 treatment had a lower stable yield than the control treatment. The cause for this result might be competition for nutrients between the plants and microorganisms that break down organic matter (Kaye and Hart 1997; Hodge et al. 2000a, 2000b). This microbial process depends on soil and weather conditions, such as the amount of soil water, soil temperature, air temperature, and precipitation (Bardgett et al. 2003; Davidson and Janssens 2006; Kuzyakov and Xu 2013; Ihara et al. 2014). Sandy soil and low precipitation do not provide favourable conditions for the activities of microbes that break down organic matter (Mengel and Kirkby 2001; Koorem et al. 2014; Fujii et al. 2018). In summary, the amounts of nutrients released and available from organic material in the study site were unfavourable for SB growth. In addition, the weather variables changed every year, which influenced the process of organic matter breakdown, leading to enhanced yield variability in the fym2 treatment compared with that in the control treatment.

Long-term effects of fertilisation regimes on SB yield

Similar to the observations of other authors (Tajnšek et al. 2013; Yang et al. 2015; Wei et al. 2016), we also found that yield was influenced by both the fertilisation regime (NPK, fym2, NPK+fym1, NPK+fym2, and NPK+straw) and the MN application rate (25, 50, 75, 100 and 125 kg) during the experimental period. The average yield over the years increased with increasing MN. However, the rate of increase in yield differed according to the OR application. The highest combined effect of MN and OR was found for the fym2 application, while there were no clearly different effects among the other OR applications, such as between fym1 and straw (Table 3 and Figure 4). The results indicated that the average SB yield increased in the nutrient application treatments in the following order: NPK+fym2 > NPK+fym1, NPK +straw or NPK > fym2 > control. However, the highest yields under NPK or fym1 application was obtained at a 50 kg ha^{-1} N supply; under the fym2 application, at a 25 kg ha^{-1} N supply; and under straw application, at a 75 kg ha^{-1} N supply. The fym2 treatment resulted in slightly lower yields than the NPK treatment, which was caused by the slow release and low utilisation efficiency of organic N. When NPK, NPK+fym1 and NPK+straw were compared, fym1 and straw did not have any advantage over the regime with NPK. The higher yield in the NPK+fym2 treatment than in the other treatments may be due not only to a greater benefit from the organic N in fym and a higher rate of additional fym supply but

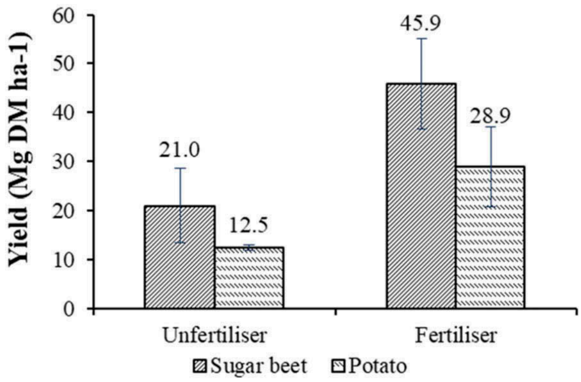


Figure 5. Yield of preceding crop (sugar beet and potato) over time. The yield in unfertilised (control), and fertiliser treatment are given.
Vertical lines indicate standard deviation (SD).

also to the improvement of other properties, e.g., soil chemical, physical and biological effects (Kismányoky and Tóth 2013). The positive effect of fym2 application was notable at lower MN supply rates (N1 and N2) (Figure 4). Hence, supplying MN to SB at low rates promoted the processes of breaking down organic matter and releasing available N for the growth of SB, resulted in an increased yield.

Due to fluctuations in precipitation among growing seasons in period (1), SB yields in the fertiliser treatment also fluctuated and drastically went down and reach the bottom in 2000, the year that was also the driest. The yield in the control gradually declined to trough in 2000. However, the SB yield for all treatments (including control) increased after 2000 (period 2). One important factor that we do not statistically evaluate but could have an important effect on SB yields and its variability is the preceding year crop. In this experiment period, all the treatments in period (1) were preceded by sugar beet and by potato in period (2). Generally, sugar beet produced higher yields (21 t ha^{-1} a^{-1} in unfertilised/ control and approximately 46 t ha^{-1} a^{-1} in fertiliser treatment) than potato (approx. 13 t ha^{-1} a^{-1} in unfertilised/ control and 29 t ha^{-1} a^{-1} on fertiliser treatments) (see Figure 5). Kunzová and Hejcman (2009, 2010) and Hejcman and Kunzová (2010) reported that the yield level of the preceding crop is an important determinant of the successive crop yield. Thus, the different biomass yields of sugar beet and potato could be implicated in the SB yield variability over time. Because preceding crop type and preceding crop yield resulted in uptake of nutrients and moisture in the soil, which related the growth of SB as a succeeding crop.

Conclusions

The SB yields were affected by fertilisation regimes, annual weather conditions, and their interactions. Mineral N fertilization decreased overall yield variability across seasons as compared to no fertilization and organic fertilization regime show higher yield variability. The combined application of MN and OR produced higher SB yields than the application of either MN or OR. At the highest SB yields were found in NPK+fym2. Greater total precipitation during the growing season (April–July) increased SB yields when supplied high MN (N > 75 kg/ha^{-1}), while at the early growth stage, a higher precipitation rate (March) and higher temperature (April or sowing day) negatively affected SB yield. One important factor that could have also influenced SB yields and yield stability is the preceding crop which could statistically evaluate in further study. The results of this analysis contribute to comprehensive crop production sustainability with regard to climate change. Further analysis of the effect of long-term fertiliser treatments on soil elements will be important for explaining the dynamics of nutrient depletion in the soil over time.

Acknowledgements

This work was financially supported by the Vietnamese Government through the 911 project. We would like to thank the Müncheberg Experimental Station, ZALF, for providing the data that were used in this analysis. Special thanks go to the current manager of the Müncheberg Experimental Station and several generations of technical staff for long-term maintenance of the experiment.

Disclosure statement

No potential conflict of interest was reported by the authors.

ORCID

Thi Huyen Thai http://orcid.org/0000-0002-9615-5095
Carsten Hoffmann http://orcid.org/0000-0001-6457-4853

References

[FAO] Food and Agriculture Organization of the United Nations. 2006. Guidelines for soil profile description. 4th ed. Rome: FAO.

[FAO] The Food and Agriculture Organization Corporate. 2019. Statistical online database; [accessed 2019 Jan 5]. http://faostat.fao.org/.

Bardgett RD, Streeter TC, Bol R. 2003. Soil microbes compete effectively with plants for organic-nitrogen inputs to temperate grasslands. Ecology. 84:1277–1287. doi:10.1890/0012-9658(2003)084[1277:SMCEWP]2.0.CO;2.

Blanchet G, Gavazov K, Bragazza L, Sinaj S. 2016. Responses of soil properties and crop yields to different inorganic and organic amendments in a Swiss conventional farming system. Agric Ecosyst Environ. 230:116–126. doi:10.1016/j.agee.2016.05.032.

BonaRes Data Portal. 2019. BonaRes: soil as a sustainable resource for the bioeconomy; [accessed 2019 Feb 25]. https://maps.bonares.de/mapapps/resources/apps/bonares/index.html?lang=en. Registration required.

Černý J, Balík J, Kulhánek M, Čásová K, Nedvěd V. 2010. Mineral and organic fertilization efficiency in long-term stationary experiments. Plant Soil Environ. 56:28–36. doi:10.17221/PSE.

Chmielewski FM, Köhn W. 1999. Impact of weather on yield components of spring cereals over 30 years. Agric For Meteorol. 96:49–58. doi:10.1016/S0168-1923(99)00047-7.

Chmielewski FM, Potts J. 1995. The relationship between crop yields from an experiment in southern England and long-term climate variations. Agric Forest Meteorol. 73:43–66. doi:10.1016/0168-1923(94)02174-I.

Davidson EA, Janssens IA. 2006. Temperature sensitivity of soil carbon decomposition and feedbacks to climate change. Nature. 440:165. doi:10.1038/nature04514.

Ellerbrock RH, Höhn A, Rogasik J. 1999. Functional analysis of soil organic matter as affected by long-term manurial treatment. Eur J Soil Sci. 50:65–71. doi:10.1046/j.1365-2389.1999.00206.x.

Ellmer F, Erekul O, Kohn W. 2001. Influence of long-term different organic-mineral fertilisation on yield, yield structure and bread-making quality of winter wheat. Arch Agron Soil Sci. 47:423–444. doi:10.1080/03650340109366226.

Evans LT. 1976. Aspects of the comparative physiology of grain yield in cereals. Adv Agron (USA). 28:301–359.

Fernandez-Getino AP, Santin-Montanya MI, Zambrana E, de Andres EF, Tenorio JL. 2015. The response of barley to rainfall and temperature in different tillage and crop rotation systems in semi-arid conditions. Ann Appl Biol. 166:143–153. doi:10.1111/aab.2015.166.issue-1.

Fisher RA. 1925. III. The influence of rainfall on the yield of wheat at Rothamsted. Philos Trans Royal Soc B. 213:89–142. doi:10.1098/rstb.1925.0003.

Freckleton RP, Watkinson AR, Webb DJ, Thomas TH. 1999. Yield of sugar beet in relation to weather and nutrients. Agric For Meteorol. 93:39–51. doi:10.1016/S0168-1923(98)00106-3.

Friedt W, Ordon F. 2013. Advance in barley sciences. In: Zhang G, Li C, Liu X, editors. Barley production and breeding in Europe: modern cultivars combine disease resistance, malting quality and high yield. Dordrecht, the Netherlands: Springer; p. 389–400.

Fujii K, Shibata M, Kitajima K, Ichi T, Kitayama K, Turner BL. 2018. Plant-soil interactions maintain biodiversity and functions of tropical forest ecosystems. Ecol Res. 33:149–160. doi:10.1007/s11284-017-1511-y.

Gomez KA, Gome AA. 1983. Statistical procedures for agricultural research. International Rice Research Institute, Philippines, 1976. A Wiley; p. 382–388.

Hakala K, Jauhiainen L, Himanen SJ, RÖTter R, Salo T, Kahiluoto H. 2012. Sensitivity of barley varieties to weather in Finland. J Agric Sci. 150:145–160. doi:10.1017/S0021859611000694.

Hejcman M, Kunzova E. 2010. Sustainability of winter wheat production on sandy-loamy Cambisol in the Czech Republic: results from a long-term fertiliser and crop rotation experiment. Field Crops Res. 115(2):191–199. doi:10.1016/j.fcr.2009.11.004.

Hodge A, Robinson D, Fitter A. 2000a. Are microorganisms more effective than plants at competing for nitrogen? Trends Plant Sci. 5:304–308. doi:10.1016/S1360-1385(00)01656-3.

Hodge A, Stewart J, Robinson D, Griffiths B, Fitter A. 2000b. Competition between roots and soil micro-organisms for nutrients from nitrogen-rich patches of varying complexity. Ecology. 88:150–164. doi:10.1046/j.1365-2745.2000.00434.x.

Hoeting JA, Madigan D, Raftery AE, Volinsky CT. 1999. Bayesian model averaging: a tutorial. Stat Sci. 382–401.

Ihara H, Kato N, Takahashi S, Nagaoka K. 2014. Effect of soil solarisation on subsequent nitrification activity at elevated temperatures. Soil Sci Plant Nutr. 60(6):824–831. doi:10.1080/00380768.2014.947233.

Kaye JP, Hart SC. 1997. Competition for nitrogen between plants and soil microorganisms. Trends Ecol Evol. 12:139–143. doi:10.1016/S0169-5347(97)01001-X.

Kismányoky T, Tóth Z. 2013. Effect of mineral and organic fertilisation on soil organic carbon content as well as on grain production of cereals in the IOSDV (ILTE) long-term field experiment, Keszthely, Hungary. Arch Agron Soil Sci. 59:1121–1131. doi:10.1080/03650340.2012.712208.

Koorem K, Gazol A, Öpik M, Moora M, Ü S, Uibopuu A, Sõber V, Zobel M. 2014. Soil nutrient content influences the abundance of soil microbes but not plant biomass at the small-scale. PLoS One. 9(3):e91998. doi:10.1371/journal.pone.0091998.

Kunzová E, Hejcman M. 2009. Yield development of winter wheat over 50 years of FYM, N, P and K fertiliser application on black earth soil in the Czech Republic. Field Crops Res. 111(3):226–234. doi:10.1016/j.fcr.2008.12.008.

Kunzová E, Hejcman M. 2010. Yield development of winter wheat over 50 years of nitrogen, phosphorus and potassium application on greyic Phaeozem in the Czech Republic. Eur J Agron. 33(3):166–174. doi:10.1016/j.eja.2010.05.002.

Kuzyakov Y, Xu X. 2013. Competition between roots and microorganisms for nitrogen: mechanisms and ecological relevance. New Phytol. 198:656–669. doi:10.1111/nph.12235.

Lobell DB, Field CB. 2007. Global scale climate–crop yield relationships and the impacts of recent warming. Environ Res Lett. 2:014002. doi:10.1088/1748-9326/2/1/014002.

Macholdt J, Piepho HP, Honermeier B. 2019. Mineral NPK and manure fertilisation affecting the yield stability of winter wheat: results from a long-term field experiment. Eur J Agron. 102:14–22. doi:10.1016/j.eja.2018.10.007.

Mengel K, Kirkby E. 2001. Principles of plant nutrition. 5th ed. Dordrecht (the Netherlands): Kluwer Academic.

Muller A, Schader C, Scialabba NE-H, Brüggemann J, Isensee A, Erb KH, Smith P, Klocke P, Leiber F, Stolze M. 2017. Strategies for feeding the world more sustainably with organic agriculture. Nat Commun. 8:1290. doi:10.1038/s41467-017-01410-w.

Peltonen-Sainio P, Jauhiainen L, Hakala K. 2011. Crop responses to temperature and precipitation according to long-term multi-location trials at high-latitude conditions. J Agric Sci. 149:49–62. doi:10.1017/S0021859610000791.

Peltonen-Sainio P, Jauhiainen L, Trnka M, Olesen JE, Calanca P, Eckersten H, Eitzinger J, Gobin A, Kersebaum KC, Kozyra J. 2010. Coincidence of variation in yield and climate in Europe. Agric Ecosyst Environ. 139:483–489. doi:10.1016/j.agee.2010.09.006.

Peltonen-Sainio P, Rajala A, Känkänen H, Hakala K. 2015. Crop physiology. In: Improving farming systems in northern Europe. 2nd ed. London, UK: Elsevier; 65–91.

Pohanková E, Hlavinka P, Orság M, Takáč J, Kersebaum K, Gobin A, Trnka M. 2018. Estimating the water use efficiency of spring barley using crop models. J Agric Sci. 156:628–644. doi:10.1017/S0021859618000060.

Příkopa M, Richter R, Zimolka J, Cerkal R. 2005. The influence of the year, fore-crops and fertilisation on yield and content of crude protein in spring barley. Plant Soil Enviro. 51:144–150. doi:10.17221/3567-PSE.

Raftery AE. 1995. Bayesian model selection in social research. Sociol Methodol. 25:111–164. doi:10.2307/271063.

Raftery AE, Madigan D, Hoeting JA. 1997. Bayesian model averaging for linear regression models. J Amer Statist Assoc. 92:179–191. doi:10.1080/01621459.1997.10473615.

Rajala A, Hakala K, Mäkelä P, Peltonen-Sainio P. 2011. Drought effect on grain number and grain weight at spike and spikelet level in six-row spring barley. J Agron Crop Sci. 197:103–112. doi:10.1111/j.1439-037X.2010.00449.x.

Russell G. 1990. Barley knowledge base: EUR-Scientific and Technical Research Reports. Brussels Luxembourg: Commission of the European Communities Catalogue No.: CD-NA–13040-EN-CECSC-EEC-EAEC. ISBN 92-826-1647-9.

Svobodová I, Misa P. 2004. Effect of drought stress on the formation of yield elements in spring barley and the potential of stress expression reduction by foliar application of fertilisers and growth stimulator. Plant Soil Environ. 50:439–446. doi:10.17221/4056-PSE.

Tajnšek A, Čergan Z, Čeh B. 2013. Results of the long-term field experiment IOSDV Jable at the beginning of the 21st century. Arch Agron Soil Sci. 59:1099–1108. doi:10.1080/03650340.2012.697996.

Timsina J. 2018. Can organic sources of nutrients increase crop yields to meet global food demand? Agronomy. 8:214. doi:10.3390/agronomy8100214.

Trnka M, Hlavinka P, Semerádová D, Dubrovský M, Žalud Z, Možný M. 2007. Agricultural drought and spring barley yields in the Czech Republic. Plant Soil Environ. 53:306–316. doi:10.17221/2210-PSE.

Trnka M, Olesen JE, Kersebaum KC, Skjelvåg AO, Eitzinger J, Seguin B, Peltonen-sainio P, Rötter R, Iglesias A, Orlandini S. 2011. Agroclimatic conditions in Europe under climate change. Glob Change Biol. 17:2298–2318. doi:10.1111/j.1365-2486.2011.02396.x.

Váňová M, Palík S, Hajšlová J, Burešová I. 2006. Grain quality and yield of spring barley in field trials under variable growing conditions. Plant Soil Environ. 52:211–219. doi:10.17221/3432-PSE.

Walter K. 2017. Crop Report No.1 German 2017 Spring Barley. German: Braugersten-Gemeinschaft e.V.; [accessed 2018 Oct 16. https://bestmalz.de/en/crop-report-1-on-german-2017-spring-barley/.

Wei W, Yan Y, Cao J, Christie P, Zhang F, Fan M. 2016. Effects of combined application of organic amendments and fertilisers on crop yield and soil organic matter: an integrated analysis of long-term experiments. Agric Ecosyst Environ. 225:86–92. doi:10.1016/j.agee.2016.04.004.

Yang J, Gao W, Ren S. 2015. Long-term effects of combined application of chemical nitrogen with organic materials on crop yields, soil organic carbon and total nitrogen in fluvo-aquic soil. Soil Till Res. 151:67–74. doi:10.1016/j.still.2015.03.008.

Zhou M, Li H, Mendham N. 2007. Combining ability of waterlogging tolerance in barley. Crop Sci. 47:278–284. doi:10.2135/cropsci2006.02.0065.