Field Crops Research 264 (2021) 108083

Contents lists available at ScienceDirect

Field Crops Research

journal homepage: www.elsevier.com/locate/fcr

Yield variability trends of winter wheat and spring barley grown during 1932–2019 in the Askov Long-term Experiment

J. Macholdt [a,b,*], S. Hadasch [c], H.-P. Piepho [c], M. Reckling [d], A. Taghizadeh-Toosi [e], B. T. Christensen [e]

[a] Professorship of Agronomy, Institute of Plant Breeding I and Agronomy, Justus-Liebig-University Giessen, Schubertstrasse 81, 35392, Giessen, Germany
[b] Section of Environmental Chemistry and Physics, Department of Plant and Environmental Sciences, University of Copenhagen, Thorvaldsensvej 40,1871 Copenhagen, Denmark
[c] Biostatistics Unit, Institute of Crop Science, University of Hohenheim, Fruwirthstrasse 23, 70599, Stuttgart, Germany
[d] Leibniz Centre for Agricultural Landscape Research (ZALF), Eberswalder Strasse 84, 15374, Muencheberg, Germany
[e] Department of Agroecology, Aarhus University, AU-Foulum, Blichers Allé 20, DK-8830, Tjele, Denmark

ARTICLE INFO

Keywords:
Cereals
Climate
Mixed model
Spring-sown crop
Winter-sown crop
Yield stability

ABSTRACT

Designing cropping systems with low yield variability (or high yield stability) is becoming increasingly important because of the ongoing climatic and agronomic challenges. The trends in yield variability under various agronomic managements can be evaluated by conducting long-term experiments. By using a novel statistical analysis method, we estimated the long-term yield variability trends for winter wheat and spring barley grown in the Askov Long-term Experiment (Denmark) with different rates of mineral fertilizers (½, 1, and 1½ NPK) and animal manure (½, 1, and 1½ AM). Yield data from 1932 to 2019 were analyzed using a mixed model approach with restricted maximum likelihood (REML)-based parameter estimates. Across all nutrient treatments, winter wheat showed lower temporal yield variability than spring barley in the first decade. However, particularly, since 2006, the wheat yield variability trend increased mainly under treatments with higher NPK rates (1 and 1½). Spring barley also showed an increasing trend in yield variability; however, compared to wheat, this trend was less pronounced. Therefore, wheat yields were less stable than barley yields during the last decade. Wheat and barley yields fluctuated more under higher NPK rates (1 and 1½) than under a reduced rate (½ NPK). In general, animal manure provided more stable yields than NPK for wheat as well as for barley. The long-term trends in yield variability of cropping systems with winter wheat and spring barley were affected by the choice of crop, nutrient source and application rate, and increasing climatic variability.

1. Introduction

Because of the concerns of climate change and global food security, the stability of agricultural systems has become as equally important as their productivity (Olesen et al., 2000). In recent years, analyses of yield stability have become more important since variations in climate are also associated with the changes in crop productivity (Lobell and Field, 2007; Najafi et al., 2018; Ray et al., 2015). Although global yield data show that productivity is stagnating in large parts of the world, trends in yield variability are more difficult to detect (Arata et al., 2020).

Analyzing trends of yield stability over long periods is crucial to capture the potential impacts of climate change and to elucidate the effects on crop management. In addition to crop choice, e.g., spring vs winter crops (Reckling et al., 2018), cropping system design and fertilization rates affect agroecosystem interactions that may play an important role in the stabilization of yields (Macholdt et al., 2019).

Resilient cropping systems can be designed by better understanding the potential trends in yield variability over time and their interactions with crop choice and management. This requires both field-level data to avoid aggregation biases (Popp et al., 2005) and novel statistical methods. Long-term agricultural field experiments (LTEs) have remarkable potential to contribute to a better understanding of yield stability (Macholdt et al., 2020b, 2020a; Reckling et al., 2018; St-Martin et al., 2017). LTEs are defined as more than 20-year-old large-scale field

* Corresponding author at: Professorship of Agronomy, Institute of Plant Breeding I and Agronomy, Justus-Liebig-University Giessen, Schubertstrasse 81, 35392, Giessen, Germany.
E-mail address: janna.macholdt@gmx.de (J. Macholdt).

https://doi.org/10.1016/j.fcr.2021.108083
Received 27 October 2020; Received in revised form 27 January 2021; Accepted 29 January 2021
Available online 12 February 2021

experiments that study crop production, nutrient cycling, and environmental impacts of agriculture (Rasmussen et al., 1998). Typically, plot treatments in LTEs remain unchanged over long time periods (Cochran, 1939), allowing the investigation of the cumulative effects and processes, requiring several years to become evident, and their separation from weather effects and climate trends. Although these properties of LTEs make them ideal for quantifying temporal variations, LTEs are only recently being used more extensively to assess yield stability (Ahrends et al., 2018). Several hundred experiments are available: 620 are listed in a global assessment by (Debreczeni and Körschens, 2003), and, in Germany alone, Grosse et al. (2020) identified a total of 205 LTEs. This resource could be exploited more effectively in the future.

Treatments within LTEs may need to be adjusted over time to avoid fossilization of general management and changes in research focus. This renders the analysis of long-term trends challenging and demands creativity in data handling and methods of yield stability analysis (Barnett et al., 1995; Barnett and Riley, 1994). Novel statistical approaches involving mixed models can be used to generate residual maximum likelihood estimates of variances and means related to trend. By using these approaches, researchers can use stability indices such as Shukla's stability variance to calculate temporal yield variability trends over time. While such approaches have been implemented for official variety trial data (Hadasch et al., 2020), they have not been used for analyzing yield data from LTEs and to reveal the effects of nutrient treatments on the changes in yield variability over time.

Herein, we estimate long-term yield variability trends for winter wheat and spring barley (1932–2019) grown with different rates of mineral fertilizer and animal manure. By applying a novel methodological approach, we tested the following hypotheses:

H1. There is an increasing trend toward more fluctuating cereal yields for winter wheat and spring barley over time.

H2. The yield variability of both crops is higher, and the increasing temporal trend of yield variability over time is greater at higher than at lower nutrient input levels.

H3. Animal manure reduces the yield variability of both crops and results in a lower increasing temporal trend of yield variability compared to mineral fertilizers.

H4. The yield variability of winter wheat is lower and the increasing temporal trend of yield variability is smaller than those for spring barley.

2. Material and methods

2.1. Experimental design and data

This study used grain yields obtained in the Askov Long-term Experiment (Askov LTE) established in Denmark in 1894. Christensen et al. (2019) provided a detailed description of the experiment. The Askov LTE compares the effect of nutrients supplied in the form of animal manure (AM) with that of N (nitrogen), P (phosphorus), and K (potassium) added as mineral fertilizers. Thus, the specific nutrient treatments are the factor of interest. Askov LTE encompasses four blocks with embedded treatment plots (row–column layout within blocks, see Fig. A1) with a harvest net plot of 36 m^2 (except one block with 20 m^2). Within each block, nutrient treatments are used in replicated plots.

In this study, we rely on grain yields of winter wheat and spring barley obtained in 1932–2019. Cereals were a part of a four-course crop rotation: winter wheat, row crops, spring barley undersown with grass–clover, and grass–clover. Over time, several experimental modifications were made, such as changes in crop species, nutrient amounts, different treatments in the blocks, and varying numbers of replicates in the different blocks (see Christensen et al., 2019 for details). We adopted an orthogonal (with respect to treatment · year classification) and robust data set that included six nutrient treatments with yield data of treatments present in all four blocks for each year. Furthermore, we defined

Table 1
Site description of the Askov LTE (1932–2019).

Location	Soil[1]	Climate[2]
Lermarken site South of Jutland Denmark 55°28′N 09°07′E 63 m a.s.l. Flat site (gradient, <2%)	• Terminal morainic deposits from the Weichsel glacial stage • Coarse sandy loam with 11 % clay (20 % clay in soil layers below 40–50 cm depth) • Plant available water in the rooting zone (0–100 cm): 164–208 mm • pH value (CaCl2): 5.6–5.7 (0–50 cm soil depth) and 4.0–4.1 (>50 cm soil depth) • Soil bulk density: 1.5–1.7 g cm-3 • Soil carbon content: 1.3 (0–20 cm soil depth) down to 0.1 (50–100 cm soil depth)	Temperate climate (annual: 8.1 °C) with cool summers (May–Aug: 14.3 °C), mild winters (Dec–Feb: 1.3 °C), and precipitation throughout the year (annual: 727 mm) mostly in autumn (Sep–Nov: 223 mm) Average annual air temperatures and precipitation of the analyzed periods[3]: • Period I (1932–1948): 8.0 °C; 641 mm • Period II (1949–1972): 7.7 °C; 698 mm • Period III (1973–2005): 8.1 °C; 720 mm • Period IV (2006–2019): 8.9 °C; 895 mm

Note: [1] Nielsen and Møberg (1984) and Sundberg et al. (1999); [2]Christensen et al. (2019); database of monthly values for mean air temperature and sum of precipitation (1932–2019) shown in Fig. 1; [3]classification of analyzed periods described in Tables 2–3.

four homogenous periods—1932–1948 (I); 1949–1972 (II); 1973–2005 (III); and 2006–2019 (IV)—that were treated separately to ensure robust data analysis.

A site description of experimental conditions at Lermarken (Askov, Denmark) is shown in Table 1, and the monthly average sum of precipitation and air temperature during the four analyzed experimental periods is shown in Fig. 1.

The six nutrient treatments selected for this study were ½ AM, 1 AM, and 1½ AM′ (animal manure) and ½ NPK, 1 NPK, and 1½ NPK (mineral fertilizer). The forms and rate of nutrients (annual average of rotation) in the treatments 1 NPK and 1 AM are shown in Tables 2 and 3. Until 1973, root crops received large nutrient inputs, whereas cereals mainly relied on residual nutrients (especially P and K). The winter wheat was supported by N mineralized from residues of grass–clover crops that are plowed just before the sowing of winter wheat. Since 1973, nutrients have been distributed more evenly among crops, and grass–clover remains without the direct inputs of any nutrient.

The average annual amount (wet weight) of animal manure applied at 1 AM was 10,000 kg ha^{-1} yr^{-1} farmyard manure plus 4000 kg ha^{-1} yr^{-1} liquid manure (1932–1972) and 25,000 kg ha^{-1} yr^{-1} for cattle slurry (1973–2019). The cattle slurry was applied to spring barley by surface spreading (immediately followed by soil plowing) in late winter or early spring. For winter wheat, cattle slurry was applied in the autumn before sowing until 1988; subsequently, it was surface-applied beneath the growing canopy in spring. Mineral fertilizer N was applied as calcium ammonium nitrate (NH_4NO_3 + $CaCO_3$; approximately 26 % N) since 1973 and as calcium nitrate ($Ca(NO_3)_2$; 16 % N) before that. Until 2006, superphosphate (approximately 8 % and 12 % S) was the P source, which was then replaced by triple phosphate (approximately 20 % P). For most years, K was applied as potassium chloride (K_2O; approximately 60 %). Mineral fertilizers were applied in March or April.

The general field managements such as soil tillage (plowing), weed control, crop protection, cultivar choice, and liming followed the rules of "good agronomic practice" and reflected the general development in conventional Danish agriculture. Thus, agronomic practices changed continuously, but only until they were adopted in general agricultural management and practice (Christensen et al., 2019). Winter wheat was sown in mid-September and spring barley in March or April. For cereal harvest (in August), an experimental plot combine (leaving 5–10 cm

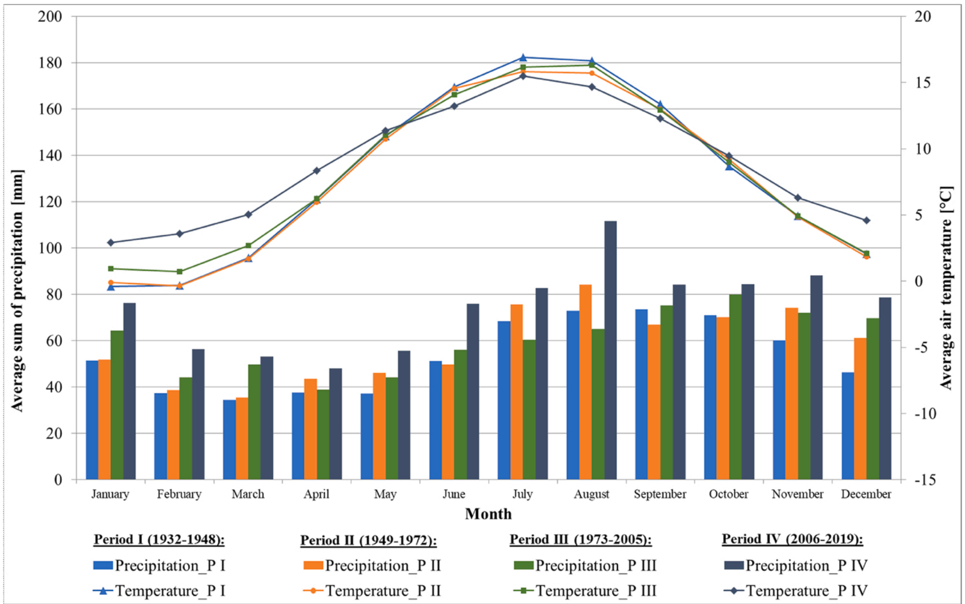

Fig. 1. Monthly average precipitation and air temperature for the four analyzed experimental periods (Askov LTE, 1932–2019).
Note: Classification of analyzed periods described in Tables 2–3.

Table 2
Experimental specifics of the analyzed experimental periods (Askov LTE, 1932–2019).

Characteristics	Periods I + II (1932–1948; 1949–1972)	Periods III + IV (1973–2005; 2006–2019)
Yield recording	Mean yield across replicates per block	Plot yield (row*column) per block
Animal manure	Farmyard manure (solid cattle dung)	Liquid manure (cattle slurry)
Fertilization (see also Table 3)	Similar nutrient supply (N, P, and K) within a crop rotation for animal manure and corresponding mineral fertilizer treatments	Similar crop-specific nutrient supply (N, P, and K) for animal manure and corresponding mineral fertilizer treatments

Table 3
Nutrients added to spring barley and winter wheat in treatments 1 NPK (mineral fertilizer) and 1 AM (animal manure) during the different experimental periods (Askov LTE, 1932–2019).

Crop	Experimental period*		1 NPK [kg ha^{-1}]			1 AM [kg ha^{-1}]		
			N	P	K	N	P	K
Spring barley	I	1932–1948	50	15	58	74	22	53
	II	1949–1972	50	16	33	30	0	0
	III	1973–2005	75	14	65	72	15	65
	IV	2006–2019	100	20	80	102	18	93
Winter wheat	I	1932–1948	68	14	57	0	0	0
	II	1949–1972	70	16	66	60	0	0
	III	1973–2005	100	19	88	96	20	92
	IV	2006–2019	150	30	120	153	26	138

Note: *periods with similar mineral N amounts at reference treatment “1 NPK”; N = nitrogen; P = phosphorus; K = potassium; animal manure (AM): farmyard manure supplemented with liquid manure to root crops and nitrogen to cereals provided as calcium nitrate (1932–1972) and cattle slurry (1973–2019) with 60–65 % of the total-N in ammonium form.

stubbles) was used. The cereal straw were removed shortly after harvest.

2.2. *Statistical analysis*

The factors of interest were “crop” (winter wheat and spring barley) and “treatment” with six nutrient treatments: “½, 1, and 1½ NPK” (mineral fertilizer) and “½, 1, and 1½ AM” (animal manure). The four experimental periods [1932–1948 (I); 1949–1972 (II); 1973–2005 (III); 2006–2019 (IV)] were analyzed separately because of different experimental characteristics (Tables 2–3) and related consequences on the statistical model setup. The statistical analyses aimed to identify differences in temporal yield variability and its development over time for the different combinations of crops, nutrient rates, and nutrient sources. The differences can be identified on the basis of the concept of Shukla’s stability variance index with the unit [t/ha]^2 (where smaller values indicate higher stability than larger values; Shukla, 1972). Furthermore, in periods III + IV, available yield data referred to individual plots (Table 2). Each block had a row–column layout (Fig. A1); hence, the factors block, row, and column were modeled as random variables and used to model blocks, rows within blocks, and columns within blocks. With this information, statistical analysis ideally accounts for the potential correlation of yields within the same plot across years (and similarly for the correlation of rows and columns across years). Another important property of this experimental design is that each of the tested crops was present in only one block in any given year (four-course rotation on four blocks). This restriction had implications for the statistical models. Hence, crop-by-year and block-by-year effects were confounded. Both the goal of the analysis and experimental specifics allowed the application of linear mixed models, accounting for all possible confounding aspects such as experimental changes in cropping sequence and cultivars (Onofri et al., 2016).

For the considered periods III and IV, we implemented a two-stage analysis in which the correlation of plots across different years was taken into account in the first stage. Based on the model in this stage, we estimated crop treatment means for the observed years and blocks. The

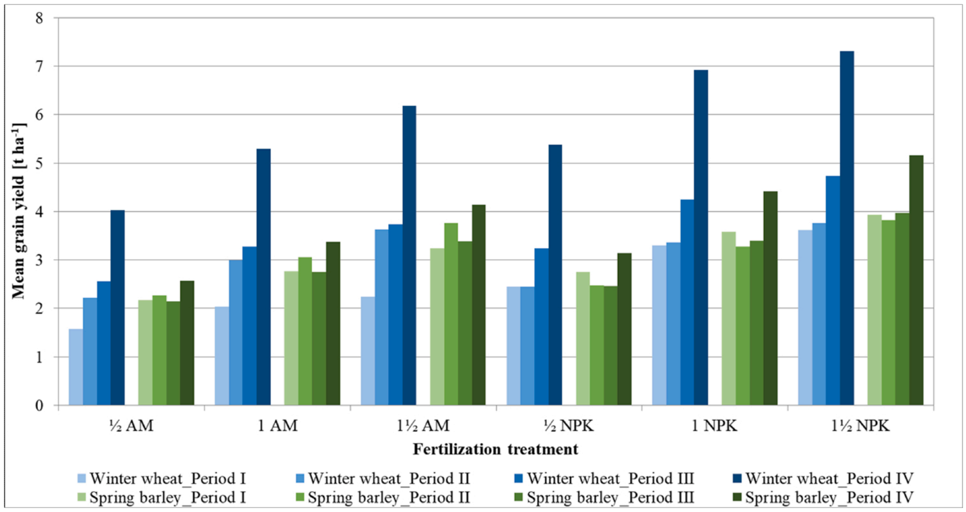

Fig. 2. The mean yield level of winter wheat and spring barley depending on the fertilization treatment and experimental period (Askov LTE, 1932–2019). Note: Period I (1932–1948); Period II (1949–1972); Period III (1973–2005); Period IV (2006–2019). Significant differences noted between crop × treatment combinations within periods are shown in Table 2.

crop treatment means were further analyzed in the second stage to estimate Shukla's stability variance and its development with time for each crop treatment combination. In the second stage, the covariance matrix of the means obtained in the first stage was considered and treated as known (Damesa et al., 2017). For periods I + II, only the second stage was applied because the yield data represented yearly means of crop treatment combinations per block (see Table 2).

For periods III + IV, the model in the first stage of the analysis is

$$y_{ijklmn} = \mu_{ijkl} + r_{klm} + c_{kln} + (rc)_{klmn} + e_{ijklmn} \tag{1}$$

where the only fixed effect is μ_{ijkl}, representing the mean yield y of crop i, treatment j, year k, and block l. The effects r_{klm}, c_{kln}, and $(rc)_{klmn}$ (see Eq. 1) are the effects for the m -th row, n -th column, and plots (row–column interaction) and were treated as normally distributed, independent random variables with zero mean and variances σ_r^2, σ_c^2, and σ_{rc}^2, respectively. Correlation over years was allowed for effects, including rows, columns, and the plot by using an autoregressive correlation (see Eqs. 2–4), indicating

$$cov(r_{klm}, r_{k'lm}) = \sigma_r^2 \phi_r^{|k-k'|} \tag{2}$$

$$cov(c_{klm}, c_{k'lm}) = \sigma_c^2 \phi_c^{|k-k'|} \tag{3}$$

$$cov\left((rc)_{klm}, (rc)_{k'lm}\right) = \sigma_{rc}^2 \phi_{rc}^{|k-k'|} \tag{4}$$

The random errors e_{ijklmn} (see Eq. 1) were assumed to be independently distributed and were thought to have homogeneous variance, σ_e^2. This model was used to estimate μ_{ijkl} and their associated covariance matrix $\boldsymbol{W}$, which in turn served as the weighting matrix in the second stage (Damesa et al., 2017).

For all four periods I–IV, the model used to estimate mean and variance trends in the second stage of the analysis is

$$\widehat{\mu}_{ijkl} = (ct)_{ij} + \beta_{ij} t_k + y_k + f_l + u_{ijkl} + v_{ijkl}\sqrt{t_k} + e_{ijkl} \tag{5}$$

where $(ct)_{ij}$ and β_{ij} represent the fixed intercept and slope, respectively, and t_k is the calendar year. All other effects are random and independent, where y_k and f_l are the effects for the calendar year and block, respectively (see Eq. 5). The effects u_{ijkl} and v_{ijkl} represent the intercept and slope needed to describe a trend in yield variance, respectively. More specifically, when they were considered as independent variables, they showed crop treatment–specific variances $\sigma_{u_{ij}}^2$ and $\sigma_{v_{ij}}^2$, respectively (see Eq. 5). The variance attributable to these effects, according to Hadasch et al. (2020), is

$$var\left(u_{ijkl} + v_{ijkl}\sqrt{t_k}\right) = \sigma_{u_{ij}}^2 + \sigma_{v_{ij}}^2 t_k \tag{6}$$

and represents the error variance in the k-th year. Therefore, the value of this quantity in the k-th year represents Shukla's stability variance. A decrease in variance was described by allowing the variance of the slope $\sigma_{v_{ij}}^2$ to become negative (see Eq. 6).

Last, in periods III + IV, e_{ijkl} (see Eq. 5) represents the error, the variance for which is assumed to be known from the first stage. More specifically, the variance matrix for the collection of all errors was assumed to be known and equal to $\boldsymbol{W}$. For periods I + II, effects for blocks f_l and errors e_{ijkl} could not be considered in the model because the available data already refer to crop treatment means for each year (see Table 2).

Statistical analysis was conducted using software R Studio Team (version 4) by using the package "asreml-R" (Butler, 2020). The corresponding model syntax is shown in Fig. A2.

3. Results

3.1. Yield level and its development over years

During period I (1932–1948), the average yield over time (≙ yield level) of spring barley was significantly higher than that of winter wheat when supplied with animal manure, whereas no significant differences was noted between the two cereal crops grown with mineral fertilizers (Figs. 2–4; Table 4). The yield level was the highest for barley receiving 1½ NPK (3.9 t/ha) and the lowest for wheat provided ½ AM (1.6 t/ha).

During the following period II (1949–1972), the yield level of spring barley and winter wheat showed no significant differences between the nutrient sources AM and NPK (Figs. 2–4; Table 4), but the average yield levels increased with increasing nutrient rate (½ < 1 < 1½).

In contrast, during period III (1973–2005), the yield level in all nutrient treatments was significantly higher for winter wheat than for spring barley. Yield differences were larger for NPK than for AM

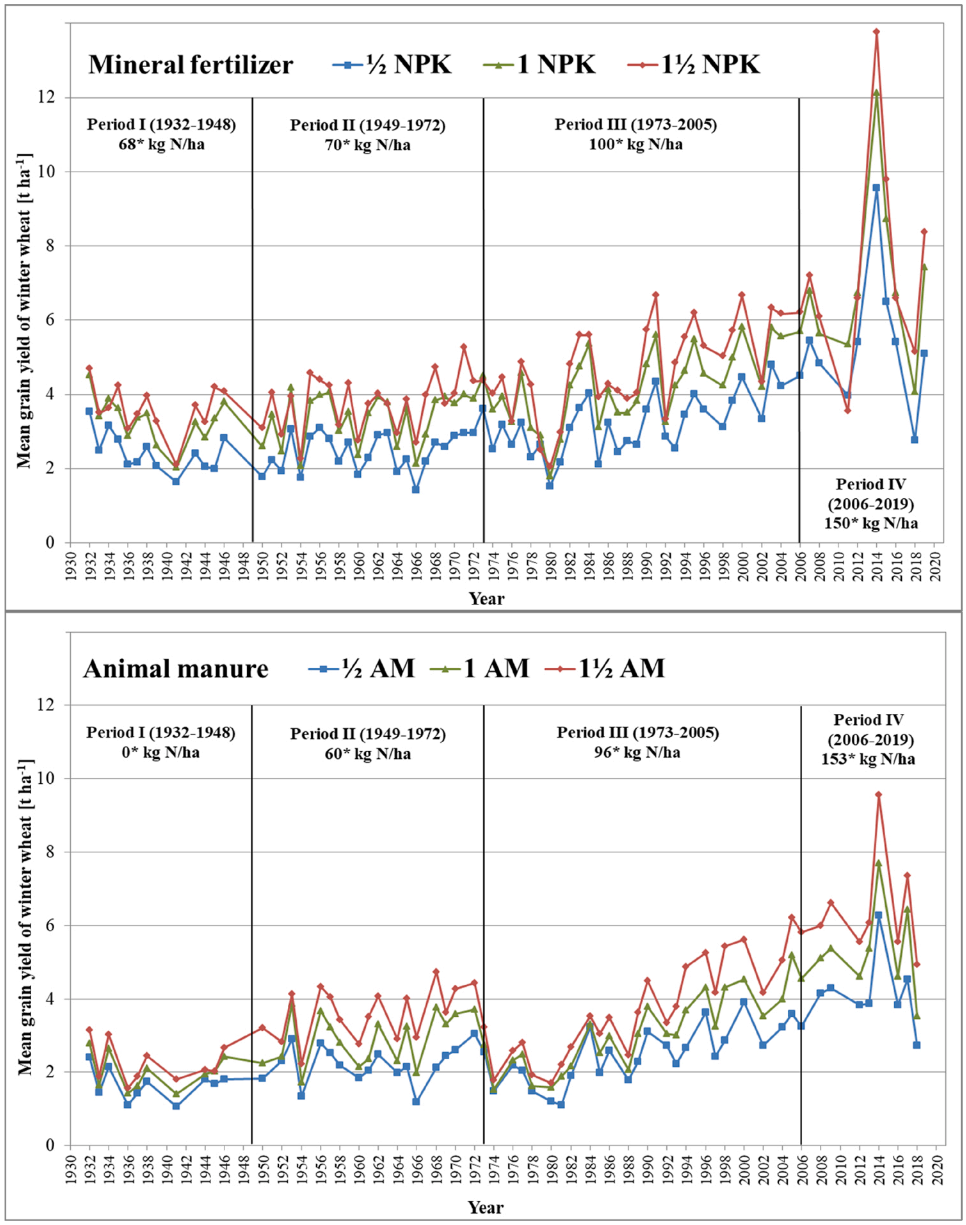

Fig. 3. Yield development of winter wheat depending on the fertilization treatment and experimental period (Askov LTE, 1932–2019).
Note: *Amount of nitrogen added in the animal manure treatment "1 AM" and mineral fertilizer treatment "1 NPK" (Table 3). Experimental periods indicated by vertical lines. Significant differences between crop × treatment combinations within periods are shown in Table 2.

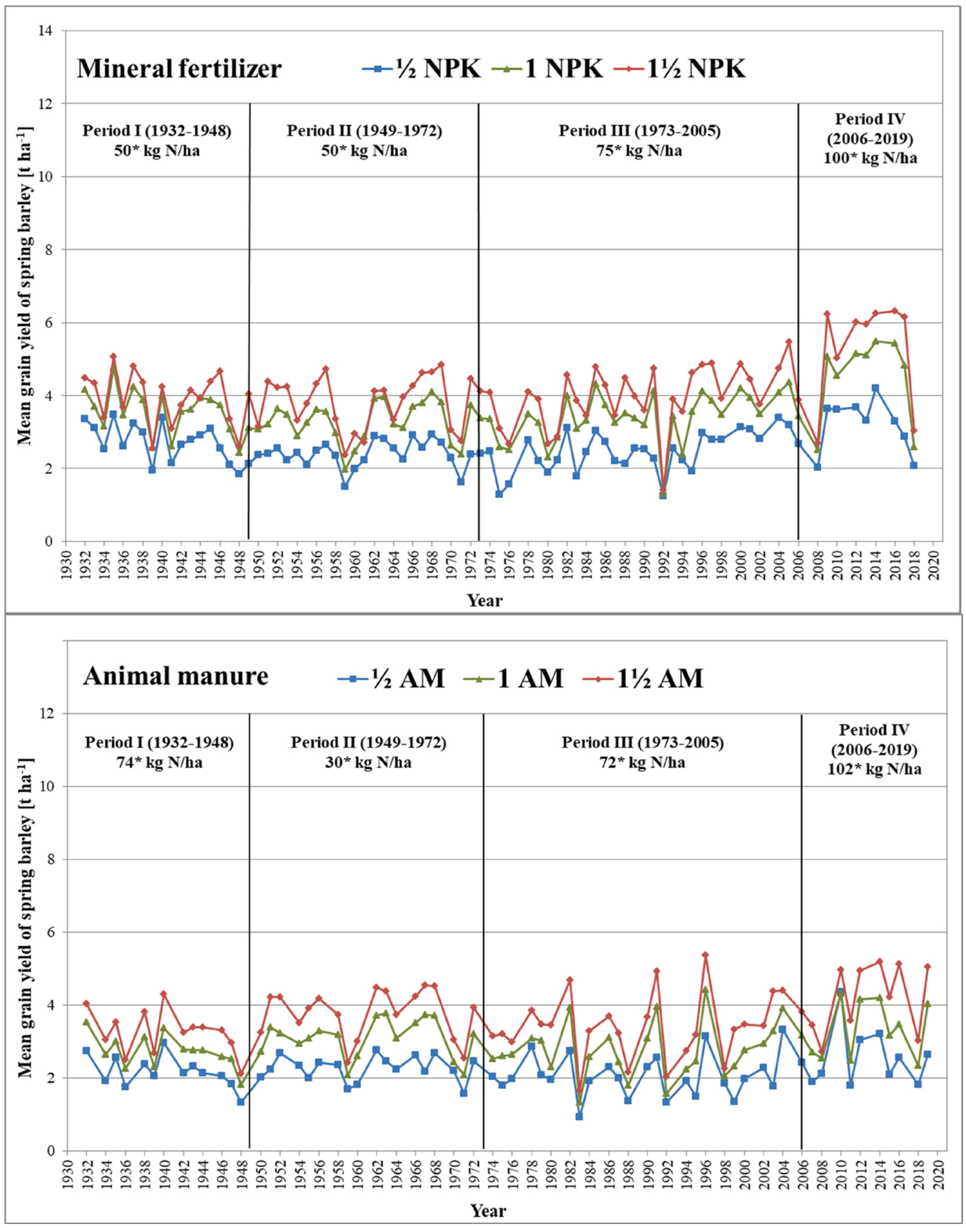

Fig. 4. Yield development of spring barley depending on the fertilization treatment and experimental period (Askov LTE, 1932–2019).
Note: *Amount of nitrogen added in the animal manure treatment "1 AM" and mineral fertilizer treatment "1 NPK" (Table 3). Experimental periods indicated by vertical lines. Significant differences between crop × treatment combinations within periods are shown in Table 2.

Table 4
Mean grain yield of winter wheat and spring barley depending on fertilization treatment and experimental period.

Period	Cereal crop	Mean grain yield [t ha-1] depending on the fertilization treatment					
		½ AM	1 AM	1½ AM	½ NPK	1 NPK	1½ NPK
1932–1948 (I)	Winter wheat	1.6^{A}	2.0^{B}	2.2^{BC}	2.5^{C}	3.3^{D}	3.6^{DE}
	Spring barley	2.2^{AB}	2.8^{CD}	3.2^{D}	2.8^{CD}	3.6^{DE}	3.9^{E}
1949–1972 (II)	Winter wheat	2.2^{A}	3.0^{B}	3.6^{C}	2.4^{A}	3.4^{BC}	3.8^{CD}
	Spring barley	2.3^{A}	3.1^{B}	3.8^{CD}	2.4^{A}	3.3^{BC}	3.8^{CD}
1973–2005 (III)	Winter wheat	2.6^{B}	3.3^{C}	3.7^{DE}	3.2^{C}	4.2^{F}	4.7^{G}
	Spring barley	2.1^{A}	2.8^{B}	3.4^{CD}	2.5^{B}	3.4^{CD}	4.0^{EF}
2006–2019 (IV)	Winter wheat	4.0^{C}	5.3^{E}	6.2^{F}	5.4^{E}	6.9^{FG}	7.3^{G}
	Spring barley	2.6^{A}	3.4^{BC}	4.1^{CD}	3.1^{AB}	4.4^{DE}	5.2^{E}

Note: Means of crop × treatment combinations (within a period) sharing no uppercase letters are significantly different ($P < 0.05$; Wald-type *t*-test). Statistical model based on Eq. 5 (see chapter 2.2 "statistical analysis").

treatments (Figs. 2–4; Table 4). Overall, yield levels were higher with NPK than with AM, with the largest wheat yield at 1½ NPK (4.7 t/ha) and the lowest barley yield at ½ AM (2.1 t/ha; Figs. 2–4; Table 4).

During period IV (2006–2019), compared with previous periods, yield differences between wheat and barley became larger, with wheat yields being significantly higher for all nutrient treatments (Figs. 2–4; Table 4). Nevertheless, the ranking of treatments remained the same as in the two earlier experimental periods: higher yield levels with NPK than with AM and increasing yields with higher nutrient rates (½ < 1 < 1½; Figs. 2–4; Table 4). This ranking was evident for both cereal crops.

3.2. Trends in temporal yield variability

During the first experimental period I (1932–1948), the temporal yield variability of winter wheat was at a low level with a minor but constant increasing trend over time at the 1 NPK rate of mineral fertilizer and was even more pronounced at 1½ NPK (Fig. 5A). Throughout this period, wheat yields were more stable with animal manure treatment (especially at ½ AM) and varied more after mineral fertilizer supply. The most unstable wheat yields were observed for 1½ NPK from 1940 onward (Fig. 5A). Spring barley showed stagnating trend lines (horizontal; no trend) during the first period, but at different levels depending on nutrient treatment (Fig. 5B). The trend lines of animal manure treatments were at low levels, indicating more stable barley yields with animal manure treatments than with mineral fertilizer treatments. The temporal yield variability of barley increased in the order ½ < 1 < 1½ and varied most for the 1½ NPK treatment. The trend line of 1½ NPK was comparably high for wheat at the end of period I (1945 onward; Fig. 5B).

During period II (1949–1972), the temporal yield variability of wheat was similarly low (indicating stable yields) and ranged from 0 to 30 $[t/ha]^2$ as in period I, with stagnating trend lines (horizontal; no trend) for nearly all treatments (Fig. 5A). Only a slight increasing trend was noted at treatment ½ AM toward more fluctuating wheat yields over time, but on a low level ($0 \rightarrow 9\ (t/ha)^2$). Moreover, after treatment with ½ NPK, a decreasing trend ($7 \rightarrow 0\ (t/ha)^2$) was observed, and wheat yields were the most stable at this treatment from 1960 onward. As in the previous period, wheat yields showed the highest temporal yield variability under increased NPK supply (1½ NPK), followed by treatments 1 NPK and 1½ AM (Fig. 5A). For spring barley, clear increasing variability trends were identified during period II, resulting in a higher temporal yield variability of barley (in all treatments) than for wheat; see, e.g., treatment 1½ NPK (Fig. 5; (A) wheat: 18; (B) barley: 90 $(t/ha)^2$). The highest nutrient levels, 1½ NPK and 1½ AM, led to the most variable barley yields, with the largest increase over time. In contrast, less varying yields with a smaller increasing trend were observed under reduced mineral fertilizer input (½ NPK), and these results were clearly the most stable under the supply of ½ AM (Fig. 5B).

Within experimental period III (1973–2005), overall higher temporal yield variabilities were noted for spring barley than for winter wheat, except for similarly nonstable yields of both crops with treatment 1½ NPK (Fig. 5). The temporal yield variability of spring barley was higher for animal manure (the highest after treatment with 1½ AM) than for mineral fertilizer. However, for winter wheat, more fluctuating yields were found with mineral NPK supply. Overall, the annual yield fluctuations for both crops increased with higher nutrient levels (½ < 1 < 1½). All variance trends were almost stagnating: the trends increased toward higher temporal yield variability over time only for wheat treated with animal manure and for barley after treatment with ½ AM (Fig. 5).

Unlike for the two previous periods, a marked increase in temporal yield variability of winter wheat occurred during period IV (2006–2019; Fig. 5A). Winter wheat clearly showed more fluctuating yields than spring barley, together with an increasing trend over time, particularly under higher mineral fertilization (1 and 1½ NPK). Compared to the highest mineral NPK input, in treatments with animal manure (1 and 1½ AM) or lower mineral fertilization (½ NPK), the increase in wheat yield variability over time (slope of trend line) was lower. For wheat, the most stable yields, with an almost stagnating trend line (horizontal; no trend), were found for ½ AM. For all treatments, spring barley (Fig. 5B) clearly showed less varying yields than wheat, unlike for the previous experimental period (1932–2005). The most stable barley yields, with no increase over time (stagnating trend line), were observed for ½ AM, 1 AM, and ½ NPK treatments. With higher rates of mineral fertilizer, particularly at 1½ NPK, barley showed a trend toward more yield fluctuations over time, but the slope was not as steep as that for wheat. Similar to the previous periods, the period 2006–2019 showed an increasing level of temporal yield variability with higher nutrient rates (½ < 1 < 1½). This effect was stronger in NPK than in AM treatments and more evident for wheat than for barley (Fig. 5). Overall, the grain yields of both crops were more stable under moderate animal manure supply and less stable with increased mineral NPK fertilization.

4. Discussion

We found an increasing trend toward higher but also more variable cereal yields over time in the Askov-LTE. For the animal manure and mineral fertilizer treatments, grain yields of wheat and barley showed a slow, but steady increase since the mid-1970s; in contrast, in the previous period, yield levels remained almost constant (Figs. 2–4; Table 4). This increase in yield level can be attributed to a combination of changes in climate; use of high-yielding crop cultivars; and improved field management, including more efficient plant protection measures, from 1973 onward. This effect was the most evident in unmanured plots, where the yield remained almost constant at approximately 1.5 t/ha and then reached 2.6 t/ha because of better varieties and field management (average 2006–2018; Christensen et al., 2019). However, any cultivar-specific effects or cultivar–treatment interactions could not be analyzed in this study because of data restrictions. With regard to the increased trend in temporal yield variability over time, new cultivars as well as improved crop protection measures do not sufficiently prepare for climatic uncertainty and variability. A similar trend toward more fluctuating cereal yields was also found within the last century by analyzing the data collected in France (Schauberger et al., 2018), Denmark (Ozturk et al., 2017), and Germany (Hadasch et al., 2020), as well as at a global scale (Döring and Reckling, 2018). In Denmark, temporal trends in the main effect variances may be attributed to a stronger variation of climatic conditions between the years, such as

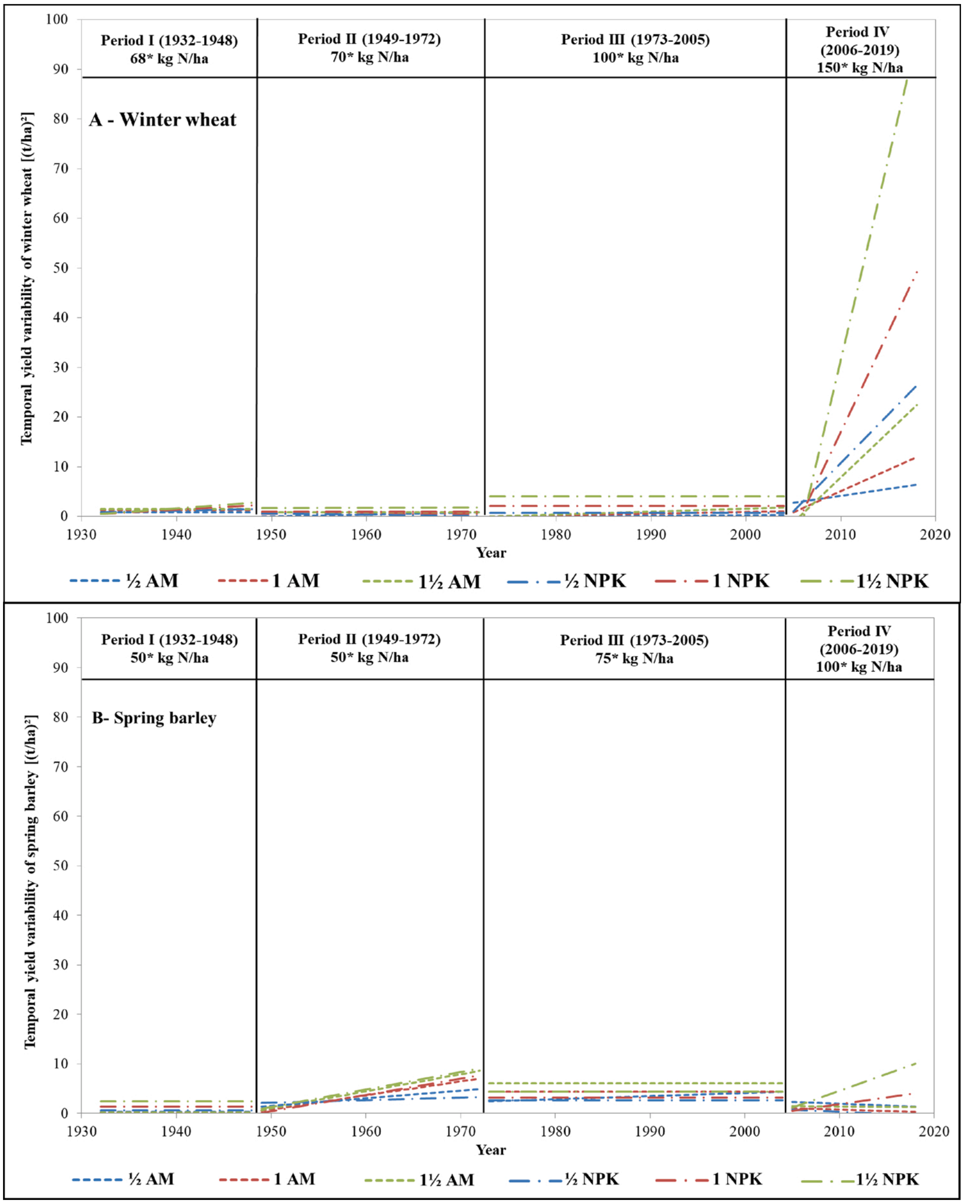

Fig. 5. Trends in temporal yield variability for winter wheat (A) and spring barley (B) by using Shukla's stability variance index in $[t/ha]^2$ (small values indicate higher stability), depending on the fertilization treatment and experimental period (Askov LTE, 1932–2019). Note: *Crop-specific reference amount of mineral nitrogen [kg N/ha] added at fertilization treatment "1 NPK" in a given period (Table 3); higher level of trend line indicates higher yield variability; lower level of trend line indicates more stable yields; slope of trend line indicates the development of yield variability over time (decrease, consistency, and increase); individual graphs for each crop treatment combination shown in Fig. A3.

extreme and more frequently occurring hot days, droughts, heavy rainfalls, and storms (Arnbjerg-Nielsen, 2006). In this study, the rise in climatic variability over time can be evidenced by (i) increasing variance of the year main effect (Table A1) and (ii) increasing variance of precipitation for the time section May–June and throughout the year (Table A2). In particular, extreme rainfall events in June and July showed strong negative influences on cereal grain yields (Olesen et al., 2000). In our study, we also observed increased summer precipitation (Fig. 1). Heavy rainfall during the growth period may cause lodging, which will reduce harvested yield and increase the risk of pest and disease outbreaks (e.g., Septoria disease) with subsequent crop losses (Peltonen-Sainio et al., 2010). Another important feature of the Askov-LTE was the continuing loss of soil carbon (C) regardless of nutrient treatment. In the B5 field, the average annual loss of soil C from the plough layer during 1923–2016 ranged from 95 to 125 kg C/ha (Christensen et al., 2019). Decreasing soil C content may impair soil water infiltration and retention (Manns and Martin, 2018), resulting in less stable yields (Schipanski et al., 2014). Other LTEs showed similar slow and long continuing C losses from arable soils of similar texture and management (Poulton et al., 2017). In the Askov-LTE, all aboveground biomass was removed after harvest, providing a small (but not sufficient) return of C in stubbles and roots apart from returning manure in the AM treatments. A long-term correlation between straw removal and less stable wheat yields was also found in the Broadbalk Wheat Experiment, Rothamsted (Macholdt et al., 2020b).

The results of this study provide ample evidence that the type and rate of nutrient inputs are the major triggers for temporal yield variability. This is underpinned by increasing yield variabilities over time with a higher nutrient input rate (½ < 1 < 1½) and the general increase in nutrient level in 1973 and 2006 (Table 3). This trend might also be coinfluenced by climatic or other environmental changes, but could not be distinguished from nutrient impact in this analysis because of the experimental setup. In recent years, 1½ NPK corresponding to 150 and 225 kg N/ha for barley and wheat, respectively, was considered above the plant optimum in the Askov-LTE. These findings are in line with those of a long-term study by Smith et al. (2007), in which temporal yield variability was lower in low-input systems than in high-input mineral fertilizer systems. In years with favorable growing conditions, plants were able to respond to higher nutrient availability and could exploit the prevailing growing conditions better, resulting in higher yield and related year-to-year variation (Lollato et al., 2019). This may partly be attributed to enhanced vegetative growth (more tillers per square meter) following larger application of N in the early spring. Therefore, cereal plants might have been more vulnerable to environmental stress, diseases, and lodging, with impacts on yield variability. However, records about these parameters are not available for validating this assumption.

We assume that N supply had the main impact on yield variability, as observed in previous studies (Chloupek et al., 2004; Varvel, 2000). Häner and Barbant (2006) showed that the impact of mineral N fertilizer on yield variation (32 %) of winter wheat was comparable to that of environmental conditions (35 %). In addition, an LTE study comparing different rates of mineral N in barley showed that yields were more stable with a lower N rate (70 kg N/ha), and yield variabilities increased with higher rates of N (140 kg N/ha; Macholdt et al., 2020a). However, this is applicable only when other nutrients and water are not limiting. In dry regions, yield stability may also be affected by water availability and nutrient inputs other than N. In contrast, other LTE studies (Macholdt et al., 2020b; Varvel, 2000) found that higher nutrient inputs (but not above optimum) led to reduced yield variability in winter wheat and corn–soybean cropping systems, respectively. Thus, a meta-analysis of LTEs, including a wider range of environments and nutrient treatments, is needed to unravel the contribution of the different factors.

The wheat and barley yields tended to be more stable under animal manure than under mineral NPK fertilization. These findings are consistent with those of the long-term studies of Guo et al. (2020); Macholdt et al. (2019), and Smith et al. (2007) in which temporal wheat yield variability was lower in manured than in mineral fertilizer systems. However, the direct effect of N at a given rate of animal manure was smaller than that at a similar rate of N in mineral fertilizers. For cattle slurry, only 60–65 % of its total N content is present as ammoniacal N at the time of application (Christensen et al., 2019), and ammonia volatilization from the surface-applied slurry may reduce the direct effect of animal manure on crop yields. Thus, the yield-stabilizing effect may not solely be attributable to the organic nature of the nutrient source but also to reduced N availability, consistent with the findings discussed above (lower nutrient rates led to more stable yields). In addition to the possible underlying N effect, animal manure may show other advantages. The application of animal manure may improve soil moisture and water-holding capacity (Manns and Martin, 2018) and increase microbial activity and soil faunal abundance (Guo et al., 2020). Animal manure may also add Ca, Mg, and micronutrients to soils (Mazur and Mazur, 2015). However, Askov-LTE is subjected to liming to maintain pH in the range of 5.5–6.5 with Ca and Mg added to all nutrient treatments.

Across all nutrient treatments, the yield variability of winter wheat was lower than that of spring barley grown during 1932–2005. Similar results have been found in yield stability analyses conducted by Reckling et al. (2018) based on LTEs conducted in the UK, Sweden, and Germany. Spring barley has shorter growth period than winter wheat and can be constrained by water deficits during crop establishment and initial growth stages, whereas winter wheat is established in autumn and regrows quickly after winter without any delays. Autumn-sown wheat has a longer growth period, benefits from precipitation over winter, has a deeper root system that allows access to water in deeper soil layers (Thorup-Kristensen et al., 2009), and matures earlier than spring barley. However, crop rotational aspects in the Askov-LTE affect the comparison of wheat and barley with potential effects on yield variability. Both crops are a part of one rotation with different positions in the cropping sequence and very different crop cycles. Winter wheat follows grass–clover and yields benefit from positive precrop effects. The positive effects on yield in rotations with grass–clover are considered to be related to an increase in soil organic matter (Johnston et al., 2009), improved soil structure (Lüscher et al., 2014), and larger amounts of soil mineral N (Müller-Stöver et al., 2012). Moreover, as perennial forages, grass–clover reduce the seed bank and storage organs of perennial weeds (Håkansson, 2003), reducing the risk of weed infestation. While the effects are greater in years one and two after the incorporation of grass-cover crop, Bergkvist and Båth (2015) found that, compared to oat yields in a rotation without leys, oat yields were still 0.3 t ha^{-1} greater even in the third season after the incorporation of grass–clover. Spring barley did not benefit from grass–clover as a precrop directly, but followed root crops and silage maize since 2005. While the crop residues of root crops may provide some residual N to the subsequent spring barley, this is not the case for silage maize (most of the aboveground biomass is harvested). Furthermore, spring barley is undersown with grass–clover, which might affect the water availability in spring in some years. Thus, compared to winter wheat, spring barley had a "rotational disadvantage," which might affect yield variability. Compared to pure grass or systems without any perennial forages, there is clear evidence for higher yields when cereals follow perennial forage legumes (Persson et al., 2008), whereas no consistent positive or negative effect is found on yield stability (Reckling et al., 2019; St-Martin et al., 2017). The different positions of crops in the cropping sequence need to be considered when comparing the results of winter wheat and spring barley, which cannot only be attributed to the differences between crop species and crop cycles alone. In the recent period (2006–2019), compared to the trends in yield variability of barley, a marked increase in wheat yield and yield variability was noted. Higher yields can be explained by an increase in nutrient addition to wheat (from 100 to 150 kg N/ha in 1 NPK and 1 AM). Changes in yield variability may be associated with an increase in nutrient application rate, changes in climate, or a combination of both; however, we did not find any clear evidence for the contribution of the impacts in this study. Although nutrients added to barley also increased (from 75 to 100 kg N ha^{-1} in 1 NPK and 1 AM), this nutrient level was still below optimum for barley and did not increase yields (and yield variability). In Denmark, there has been a tendency for increased precipitation in autumn over recent decades (Kristensen et al., 2011), as has also been observed in this study (Fig. 1). This might have resulted in an increasing trend in higher temporal yield variability for winter wheat (particularly since 2006; Fig. 5A), which was attributed to the wet, unfavorable soil conditions for sowing in autumn and associated delayed or disturbed seed emergence or early growing stages (Thorup-Kristensen et al., 2009). These changes did not affect spring-sown barley, which, compared to winter wheat, showed lower increasing trend in yield variability (Fig. 5B).

5. Conclusion

In the Askov-LTE, the long-term yield variability trends of winter wheat and spring barley were mainly affected by the level of nutrient input (½, 1, and 1½), nutrient source (mineral NPK vs animal manure), time (four periods: 1932–1948; 1949–1972; 1973–2005; 2006–2019), and their combinations. Regarding the development of yield variability over time, an increasing trend toward more fluctuating cereal yields across all nutrient treatments was noted (hypothesis H1 accepted). This was more pronounced for winter wheat than for spring barley and more pronounced for higher rates of mineral fertilizer than for lower animal manure supply. A higher level of nutrient input (1½) led to larger fluctuation of cereal yields with an increasing trend over time. In addition, the temporal yield variability and its trend were lower in treatments with reduced nutrient inputs (½). This effect occurred equally for both crops and for both nutrient sources (AM and NPK; hypothesis H2 accepted). Overall, compared to mineral fertilizer for most observations, wheat and barley yields were less variable and showed smaller increasing trends under animal manure supply (hypothesis H3 accepted). We conclude that wheat yields tended to be more stable than barley yields for most of the experimental period and for all nutrient treatments, except for the more recent period 2006–2019. In this period, we identified a marked increase in wheat yield variability and comparably less variable barley yields (hypothesis H4 partly accepted). These novel findings suggest that further investigations targeted at elucidating the fundamental processes and adaptation options are needed to make crops more resilient in the future. Comparable LTEs or yield simulation studies based on agroecosystem models may be analyzed using a similar statistical approach to evaluate the validity of our findings under different soil, future climate, and various agronomic management conditions.

This study revealed a promising methodological approach to handle complex LTE datasets by analyzing subperiods separately, by using a mixed-model providing residual maximum likelihood estimates and by refining Shukla's stability variance index for calculating the long-term trends in yield variability. This approach provides a wide range of applications in the context of cropping system sustainability and resilience in terms of climate change. One opportunity is to evaluate the temporal yield variability in crop rotations by normalizing the yields per period and treatment. Another option is to analyze the entire crop rotational yields, including the calculation of the probability of rotational yields falling below a certain yield or economic threshold (risk analysis). Furthermore, this novel statistical approach can be used for analyzing other LTEs such as long-term grassland experiments in terms of “impact of botanical composition/species diversity on the temporal development of biomass yield variability” depending on nutrient regimes or other treatments. These kinds of stability and risk analyses are of direct importance for farmers, because the results can be used for adapting management practices and for improving cropping systems to obtain reliably high and stable yields.

Financial support

The first (JM), third (HP), and fourth (MR) authors acknowledge the support by Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) grants (Project numbers 419973621, 420661662, and 324840916, respectively). We also thank the DFG for funding the young scientist academy on Agroecosystem Research and Plant Production 2018–2019 that supported MR and JM and initiated the collaboration between projects.

Ethical standards

Not applicable.

Statement of data availability

The dataset used in this study was provided by Aarhus University, Denmark. The dataset is not publicly available, but may be obtained from the last authors (AT and BC) upon reasonable request and with the permission of the mentioned institution.

CRediT authorship contribution statement

J. Macholdt: Conceptualization, Formal analysis, Methodology, Writing - original draft, Writing - review & editing. **S. Hadasch:** Methodology, Formal analysis, Writing - review & editing. **H.-P. Piepho:** Methodology, Formal analysis, Writing - review & editing. **M. Reckling:** Writing - original draft, Writing - review & editing. **A. Taghizadeh-Toosi:** Data curation, Conceptualization, Writing - review & editing. **B. T. Christensen:** Conceptualization, Data curation, 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.

Acknowledgment

We gratefully acknowledge the excellent technical assistance provided by the staff at Askov Experimental Station.

Appendix A

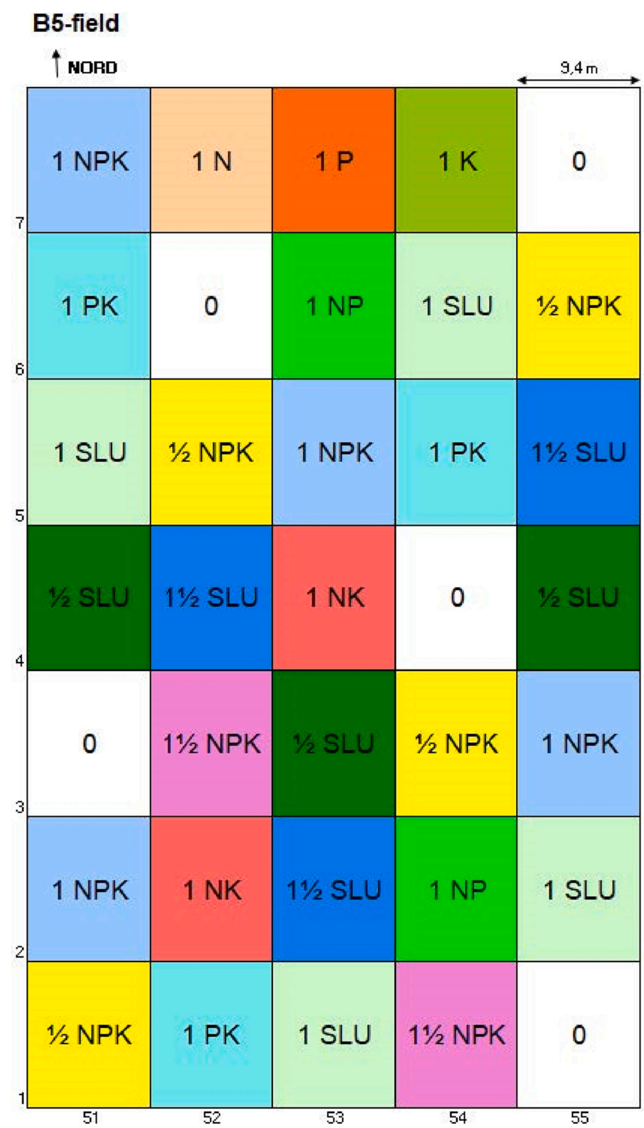

Fig. A1. Experimental design of the Askov LTE showing the distribution of treatment replicates within a block (= field, here by example of the so-called B5-field). Row and column numbers identify individual plots. The analyzed plots used in this study are ½ NPK, 1 NPK, 1½ NPK, ½ SLU, 1 SLU, and 1½ SLU. Animal manure (AM) is indicated by slurry (SLU).
Source: Christensen et al. (2019). The entire field plan with all four block designs has been provided in the Askov-LTE DCA report 151 (pages 23–25; Figs. 3–6), which is available online via DCArapport151.pdf (au.dk).

```
rm(list=ls())
require(asreml)
require(xlsx)
require(stringi)

data=read.xlsx("< path to file >")
data$year=as.factor(data$year)
data$crop=as.factor(data$crop)
data$treatment=as.factor(data$treatment)
data$field=as.factor(data$field)
data$column=as.factor(data$column)
data$row=as.factor(data$row)
data$plot=as.factor(data$plot)

#get starting values by using start.values = T
asr=asreml(fixed=yield ~ crop+year+crop:year+crop:treatment:year:field,
        random=~field:row:ar1(year)+field:column:ar1(year)+field:row:column:ar1(year),
        options=asreml.options(workspace=8e8),
        start.values = T,
        data=data)
#set constraints of AR variance components to positive "P"
start_val=asr$vparameters.table
start_val[which(start_val$Constraint=="U"),"Constraint"]="P"

#fit model with new variance component constraints using G.param=...
asr=asreml(fixed=yield ~ crop+year+crop:year+crop:treatment:year:field,
        random=~field:row:ar1(year)+field:column:ar1(year)+field:row:column:ar1(year),
        options=asreml.options(workspace=8e8,maxit=100),
        G.param = start_val,
        data=data)
#update if not converged or if change of variance components larger than 1%
while (length(which(summary(asr)$varcomp$"%ch">1))) {asr=update(asr)}

#get means and their covariance matrix for the second stage
p=predict.asreml(asr,classify="crop:treatment:year:field",vcov=T,options=asreml.options(pworkspace=8e8))
#means
means=p$pvals
#covariance matrix of means
inv_XVX=as.matrix(p$vcov)
#remove empty rows and cols
inv_XVX=inv_XVX[which(is.na(means$predicted.value)==F),][,which(is.na(means$predicted.value)==F)]
means=means[which(is.na(means$predicted.value)==F),]

# create new variables in the dataset
data$ct=as.factor(paste(data$crop,data$treatment,sep=" ")) # just done to simplify the model synthax
data$t=as.numeric(as.character(data$year)) # needed for the regression on time
data$sqrt_t=sqrt((data$t-min(data$t))*1) # needed for the linear variance trends

# create user-defined variance function with inputs (order, kappa) as required (see ASREML user manual)
fun=function(order,kappa) {
  V=as.matrix(kappa*inv_XVX) # user defined variance matrix
  dV=as.matrix(inv_XVX) # derivative of user defined variance matrix
  return(list(V,dV))
}

# start with a model that has only positive variance trends (positive coefficients for at(ct):year:sqrt_t)
# if not done and all variance trends are allowed to become negative, singularity issues may arise
asr=asreml(fixed=predicted.value ~ -1+ct+ct:t,
        random=~year+field+
          at(ct):year+
          at(ct):year:sqrt_t,
        residual = ~ own(units, "fun",1,con="F", type="R"),
        family = asr_gaussian(dispersion=1),
        data=data)

# check which variance components for "at(ct):year:sqrt_t" are close to zero because they should be allowed to become negative
summary(asr_update)$varcomp

#change the constraints of variance components which are close to zero
G.param=asr$G.param
G.param$`at(ct, 3 9):year:sqrt_t`$variance$con="U"
G.param$`at(ct, 3 10):year:sqrt_t`$variance$con="U"
G.param$`at(ct, 4 3):year:sqrt_t`$variance$con="U"
G.param$`at(ct, 4 4):year:sqrt_t`$variance$con="U"
G.param$`at(ct, 4 8):year:sqrt_t`$variance$con="U"
G.param$`at(ct, 4 10):year:sqrt_t`$variance$con="U"

# fit model again with the new constraints using G.param=...
asr_update=asreml(fixed=predicted.value ~ -1+ct+ct:t,
              random=~year+field+
                at(ct):year+
                at(ct):year:sqrt_t,
              residual = ~ own(units, "fun",1,con="F", type="R"),
              family = asr_gaussian(dispersion=1),
              G.param = G.param,
              data=data)
asr_update=update(asr_update)
vc=summary(asr_update)$varcomp
```

Fig. A2. Model syntax (RStudio Team, 2020) used for statistical analysis (Askov LTE, 1932–2019).

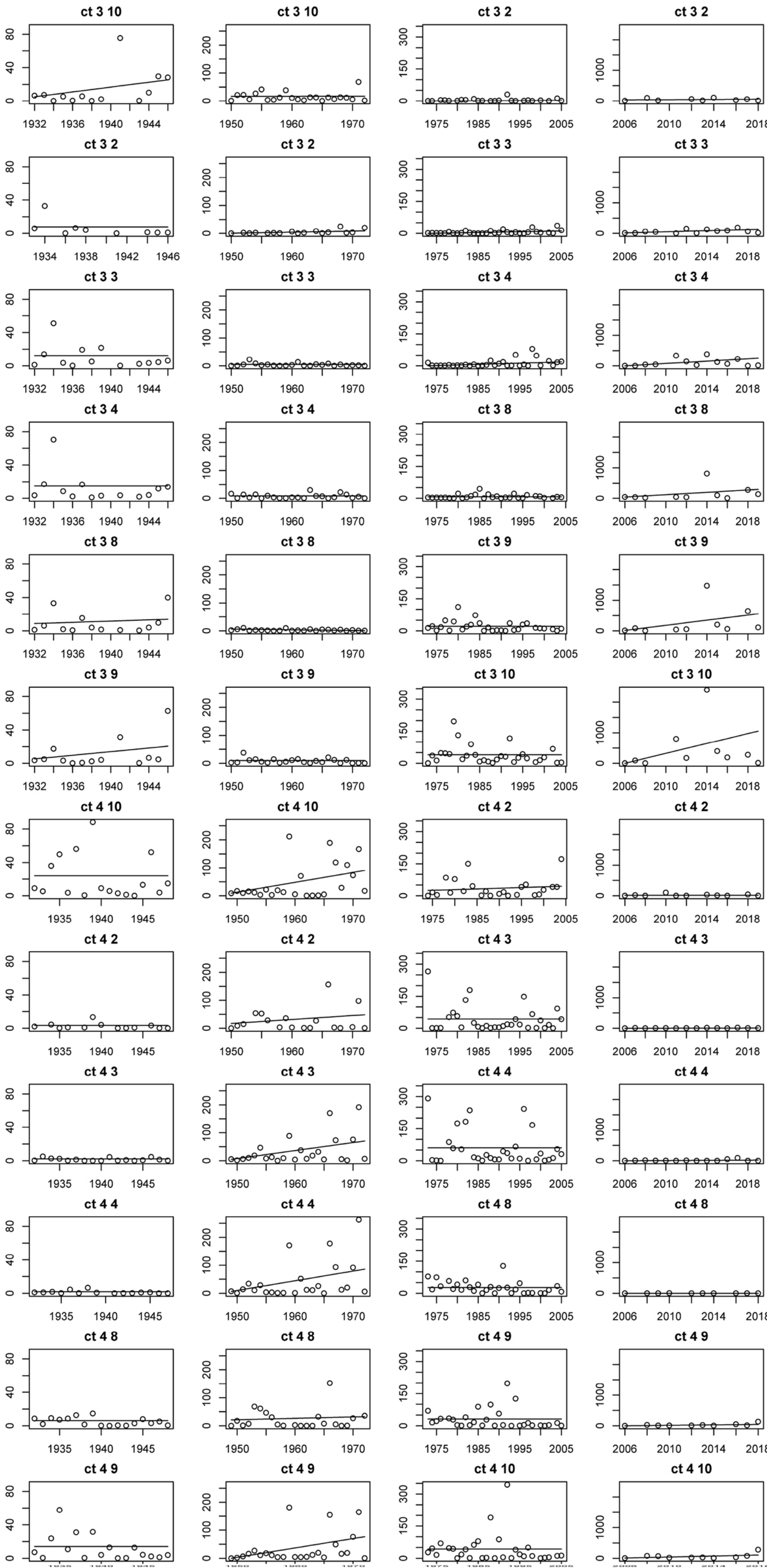

Fig. A3. Trends in temporal yield variability for winter wheat and spring barley depending on fertilization treatments and experimental periods (Askov LTE, 1932–2019).

Note: Abbreviations on the top of each graph: the first number indicates the crop “c” (3 = winter wheat; 4 = spring barley); the second number indicates the fertilization treatment “t” (2 = ½ AM; 3 = 1 AM; 4 = 1½ AM; 8 = ½ NPK, 9 = 1 NPK; 10 = 1½ NPK); yield variance (squared residuals on y-axis with unit = $(dt/ha)^2$) plotted against time (on x-axis with unit = years).

Table A1
Variance of the year main effect depending on the experimental period (Askov LTE, 1932–2019).

Period	Year main effect	
	Variance estimate	Standard error
1932–1948 (I)	16.06	6.10
1949–1972 (II)	19.59	6.05
1973–2005 (III)	24.18	6.62
2006–2019 (IV)	58.79	25.24

Note: Analysis based on the statistical model as shown in Fig. A2.

Table A2
Variance in precipitation depending on the experimental period (Askov LTE, 1932–2019).

Period	Variance of precipitation sum [mm^2]	
	Time section May–June	Annual
1932–1948 (I)	614	885
1949–1972 (II)	393	852
1973–2005 (III)	779	928
2006–2019 (IV)	934	1431

Note: Values based on the climate diagram are shown in Fig. 1.

References

Ahrends, H.E., Eugster, W., Gaiser, T., Rueda-Ayala, V., Hüging, H., Ewert, F., Siebert, S., 2018. Genetic yield gains of winter wheat in Germany over more than 100 years (1895–2007) under contrasting fertilizer applications. Environ. Res. Lett. 13, 104003. https://doi.org/10.1088/1748-9326/aade12.

Arata, L., Fabrizi, E., Sckokai, P., 2020. A worldwide analysis of trend in crop yields and yield variability: evidence from FAO data. Econ. Model. 90, 190–208. https://doi.org/10.1016/j.econmod.2020.05.006.

Arnbjerg-Nielsen, K., 2006. Significant climate change of extreme rainfall in Denmark. Water Sci. Technol. 54, 1–8. https://doi.org/10.2166/wst.2006.572.

Barnett, V., Riley, J., 1994. Statistics for environmental change. Exp. Agric. 31, 117–130. https://doi.org/10.1017/S0014479700025217.

Barnett, V., Landau, S., Welham, S.J., 1995. Measuring sustainability. Ecol. Environ. Stat. 1, 21–36. https://doi.org/10.1007/BF00714195.

Bergkvist, G., Båth, B., 2015. Nitrogen fertiliser dose influence the effect of two year rotational leys with grass or clover/grass on other crops in the rotation. Asp. Appl. Biol. 128, 133–139.

Butler, D., 2020. asreml: Fits the Linear Mixed Model. R package version 4.1.0.130. Online available (accessed 27/10/2020. https://www.vsni.co.uk.

Chloupek, O., Hrstkova, P., Schweigert, P., 2004. Yield and its stability, crop diversity, adaptability and response to climate change, weather and fertilisation over 75 years in the czech republic in comparison to some European countries. Field Crops Res. 85, 167–190. https://doi.org/10.1016/S0378-4290(03)00162-X.

Christensen, B.T., Thomsen, I.K., Eriksen, J., 2019. The Askov Long-term Experiment: 1894-2019 - a Unique Research Platform Turns 125 Years. DCA Report No. 151. Online available (accessed 26/08/2020). Danish Centre for Food and Agriculture (DCA), Denmark. https://dcapub.au.dk/djfpublikation/djfpdf/DCArapport151.pdf.

Cochran, W.G., 1939. Long-term agricultural experiments. J. R. Stat. Soc. 6, 104–140. https://doi.org/10.2307/2983686.

Damesa, T., Worku, M., Möhring, J., Piepho, H.-P., 2017. One step at a time: stage-wise analysis of a series of experiments. Agron. J. 109, 845–857. https://doi.org/10.2134/agronj2016.07.0395.

Debreczeni, K., Körschens, M., 2003. Long-term field experiments of the world. Arch. Agron. Soil Sci. 49, 465–483. https://doi.org/10.1080/03650340310001594754.

Döring, T.F., Reckling, M., 2018. Detecting global trends of cereal yield stability by adjusting the coefficient of variation. Eur. J. Agron. 99, 30–36. https://doi.org/10.1016/j.eja.2018.06.007.

Grosse, M., Hierold, W., Ahlborn, M.C., Helming, K., 2020. Long-term field experiments in Germany: classification and spatial representation. Soil Discuss. 2020, 1–32. https://doi.org/10.5194/soil-2020-30.

Guo, Z., Wan, S., Hua, K., Yin, Y., Chu, H.Y., Wang, D., Guo, X., 2020. Fertilization regime has a greater effect on soil microbial community structure than crop rotation and growth stage in an agroecosystem. Appl. Soil Ecol. 149, 103510 https://doi.org/10.1016/j.apsoil.2020.103510.

Hadasch, S., Laidig, F., Macholdt, J., Bönecke, E., Piepho, H.-P., 2020. Trends in mean performance and stability of winter wheat and winter rye yields in a long-term series of variety trials. Field Crops Res. 152, 107792 https://doi.org/10.1016/j.fcr.2020.107792.

Håkansson, S., 2003. Weeds and Weed Management on Arable Land: An Ecological Approach. CABI Publishing, Wallingford, UK. https://doi.org/10.1017/S0014479704251791.

Häner, L.L., Barbant, C., 2006. The art of splitting nitrogen applications to optimise wheat yield and protein content. Agroresearch Suisse 7, 80–87. Available online (accessed 26/08/2020). https://www.agrarforschungschweiz.ch/en/2016/02/the-art-of-splitting-nitrogen-applications-to-optimise-wheat-yield-and-protein-content/.

Johnston, A.E., Poulton, P.R., Coleman, K., 2009. Soil organic matter: its importance in sustainable agriculture and carbon dioxide fluxes. Adv. Agron. 101, 1–57. https://doi.org/10.1016/S0065-2113(08)00801-8.

Kristensen, K., Schelde, K., Olesen, J.E., 2011. Winter wheat yield response to climate variability in Denmark. J. Agric. Sci. 149, 33–47. https://doi.org/10.1017/S0021859610000675.

Lobell, D.B., Field, C.B., 2007. Global scale climate–crop yield relationships and the impacts of recent warming. Environ. Res. Lett. 2, 1–7. https://doi.org/10.1088/1748-9326/2/1/011002.

Lollato, R.P., Figueiredo, B.M., Dhillon, J.S., Arnall, D.B., 2019. Wheat grain yield and grain-nitrogen relationships as affected by N, P, and K fertilization: a synthesis of long-term experiments. Field Crops Res. 236, 42–57. https://doi.org/10.1016/j.fcr.2019.03.005.

Lüscher, A., Mueller-Harvey, I., Soussana, J.F., Rees, R.M., Peyraud, J.L., 2014. Potential of legume-based grassland–livestock systems in Europe: a review. Grass Forage Sci. 69, 206–228. https://doi.org/10.1111/gfs.12124.

Macholdt, J., Piepho, H.-P., Honermeier, B., 2019. Does fertilization impact production risk and yield stability across an entire crop rotation? Insights from a long-term experiment. Field Crops Res. 238, 82–92. https://doi.org/10.1016/j.fcr.2019.04.014.

Macholdt, J., Styczen, M., Macdonald, A., Piepho, H.-P., Honermeier, B., 2020a. Long-term analysis from a cropping system perspective: yield stability, environmental adaptability, and production risk of winter barley. Eur. J. Agron. 117, 126056. https://doi.org/10.1016/j.eja.2020.126056.

Macholdt, J., Piepho, H.-P., Honermeier, B., Perryman, S., Macdonald, A., Poulton, P., 2020b. The effects of cropping sequence, fertilization and straw management on the yield stability of winter wheat (1986–2017) in the Broadbalk Wheat Experiment, Rothamsted, UK. J. Agric. Sci. 158, 65–79. https://doi.org/10.1017/S0021859620000301.

Manns, H.R., Martin, R.C., 2018. Cropping system yield stability in response to plant diversity and soil organic carbon in temperate ecosystems. Agroecol. Sustain. Food Syst. 42, 24–750. https://doi.org/10.1080/21683565.2017.1423529.

Mazur, Z., Mazur, T., 2015. Influence of long-term fertilization on phosphorus, potassium, magnesium, and sulphur content in soil. Polish J. Environ. Stud. 24, 185–190. https://doi.org/10.15244/pjoes/29203.

Müller-Stöver, D., Hauggaard-Nielsen, H., Eriksen, J., Ambus, P., Johansen, A., 2012. Microbial biomass, microbial diversity, soil carbon storage, and stability after incubation of soil from grass–clover pastures of different age. Biol. Fertil. Soils 48, 371–383. https://doi.org/10.1007/s00374-011-0633-6.

Najafi, E., Devineni, N., Khanbilvardi, R.M., Kogan, F., 2018. Understanding the Changes in Global Crop Yields Through Changes in Climate and Technology. Earth's Future 6, 410–427. https://doi.org/10.1002/2017EF000690.

Nielsen, J.D., Møberg, J.P., 1984. Classification of 5 soil profiles from experimental stations in Denmark (in Danish with English summary). Tidskrift for Planteavl 88, 155–167.

Olesen, J.E., Jensen, T., Petersen, J., 2000. Sensitivity of field-scale winter wheat production in Denmark to climate variability and climate change. Clim. Res. 15 https://doi.org/221-23810.3354/cr015221.

Onofri, A., Seddaiu, G., Piepho, H.-P., 2016. Long-term experiments with cropping systems: case studies on data analysis. Eur. J. Agron. 77, 223–235. https://doi.org/10.1016/j.eja.2016.02.005.

Ozturk, I., Sharif, B., Baby, S., Jabloun, M., Olesen, J.E., 2017. The long-term effect of climate change on productivity of winter wheat in Denmark: a scenario analysis using three crop models. J. Agric. Sci. 155, 733–750. https://doi.org/10.1017/S0021859616001040.

Peltonen-Sainio, P., Jauhiainen, L., Trnka, M., Olesen, J.E., Calanca, P., Eckersten, H., Eitzinger, J., Gobin, A., Kersebaum, K.C., Kozyra, J., Kumar, S., Marta, A.D., Micale, F., Schaap, B., Seguin, B., Skjelvåg, A.O., Orlandini, S., 2010. Coincidence of variation in yield and climate in Europe. Agric. Ecosyst. Environ. 139, 483–489. https://doi.org/10.1016/j.agee.2010.09.006.

Persson, T., Bergkvist, G., Kätterer, T., 2008. Long-term effects of crop rotations with and without perennial leys on soil carbon stocks and grain yields of winter wheat. Nutr. Cycl. Agroecosystems 81, 193–202. https://doi.org/10.1007/s10705-007-9144-0.

Popp, M., Rudstrom, M., Manning, P., 2005. Spatial yield risk across region, crop and aggregation method. Can. J. Agric. Econ. 53, 103–115. https://doi.org/10.1111/j.1744-7976.2005.00408.x.

Poulton, P., Johnston, J., Macdonald, A., White, R., Powlson, D., 2017. Major limitations to achieving "4 per 1000" increases in soil organic carbon stocks in temperate regions: Evidence from long-term experiments at Rothamsted Research, United Kingdom. Glob. Change Biol. 24, 2563–2584. https://doi.org/10.1111/gcb.14066.

Rasmussen, P.E., Goulding, K.W.T., Brown, J.R., Grace, P.R., Janzen, H.H., Korschens, M., 1998. Long-term agroecosystem experiments: assessing agricultural sustainability and global change. Science 282, 893–896. http://www.jstor.org/stable/2897444.

Reckling, M., Döring, T.F., Bergkvist, G., Stoddard, F.L., Watson, C.A., Seddig, S., Chmielewski, F.-M., Bachinger, J., 2018. Grain legume yields are as stable as other spring crops in long-term experiments across northern Europe. Agron. Sustain. Dev. 38, 63. https://doi.org/10.1007/s13593-018-0541-3.

Ray, D.K., Gerber, J.S., MacDonald, G.K., West, P., 2015. Climate variation explains a third of global crop yield variability. Nat. Commun. 6, 5989. https://doi.org/10.1038/ncomms6989.

Reckling, M., Albertsson, J., Topp, C.F.E., Vermue, A., Carlsson, G., Watson, C., Justes, E., Bergkvist, G., Jensen, E.S., 2019. Does cropping system diversification with legumes lead to higher yield stability? Diverging evidence from long-term experiments across

Europe. In: European Conference on Crop Diversification. September 18-21 September 2019, Budapest, Hungary. Available online (accessed 27/20/2020. https://www.researchgate.net/publication/335925563_Does_cropping_system_diversification_with_legumes_lead_to_higher_yield_stability_Diverging_evidence_from_long-term_experiments_across_Europe.

RStudio Team, 2020. RStudio: Integrated Development for R. RStudio. URL. PBC, Boston, MA. http://www.rstudio.com/.

Schauberger, B., Ben-Ari, T., Makowski, D., Kato, T., Kato, H., Ciais, P., 2018. Yield trends, variability and stagnation analysis of major crops in France over more than a century. Sci. Rep. 8, 16865. https://doi.org/10.1038/s41598-018-35351-1.

Schipanski, M.E., Smith, R.G., Pisani Gareau, T.L., Jabbour, R., Lewis, D.B., Barbercheck, M.E., Mortensen, D.A., Kaye, J.P., 2014. Multivariate relationships influencing crop yields during the transition to organic management. Agric. Ecosyst. Environ. 189, 119–126. https://doi.org/10.1016/j.agee.2014.03.037.

Shukla, G.K., 1972. Some statistical aspects of partitioning genotype-environmental components of variability. Heredity 29, 237–245. https://doi.org/10.1038/hdy.1972.87.

Smith, R.G., Menalled, F.D., Robertson, G.P., 2007. Temporal yield variability under conventional and alternative management systems. Agron. J. 99, 1629–1634. https://doi.org/10.2134/agronj2007.0096.

St-Martin, A., Vico, G., Bergkvist, G., Bommarco, R., 2017. Diverse cropping systems enhanced yield but did not improve yield stability in a 52-year long experiment. Agric. Ecosyst. Environ. 247, 337–342. https://doi.org/10.1016/j.agee.2017.07.013.

Sundberg, P.S., Callesen, I., Greve, M.H., Raulung-Rasmussen, K., 1999. Danish Soil Profiles. Denmarks Jordbrugs Forskning, Tjele, Denmark.

Thorup-Kristensen, K., Cortasa, M.S., Loges, R., 2009. Winter wheat roots grow twice as deep as spring wheat roots, is this important for N uptake and N leaching losses? Plant Soil 322, 101–114. https://doi.org/10.1007/s11104-009-9898-z.

Varvel, G.E., 2000. Crop rotation and nitrogen effects on normalized grain yields in a long-term study. Agron. J. 92, 938–941. https://doi.org/10.2134/agronj2000.925938x.