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Nutrient supply affects the yield stability of major European crops—a 50 year study

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Abstract

Yield stability is important for food security and a sustainable crop production, especially under changing climatic conditions. It is well known that the variability of yields is linked to changes in meteorological conditions. However, little is known about the long-term effects of agronomic management strategies, such as the supply of important nutrients. We analysed the stability of four major European crops grown between 1955 and 2008 at a long-term fertilization experiment located in Germany. Six fertilizer treatments ranged from no fertilization over the omission of individual macronutrients to complete mineral fertilization with all major macronutrients (nitrogen, phosphorus, potassium and calcium). Yield stability was estimated for each crop × treatment combination using the relative yield deviation in each year from the corresponding (nonlinear) trend value (relative yield anomalies (RYA)). Stability was lowest for potato, followed by sugar beet and winter wheat and highest for winter rye. Stability was highest when soils had received all nutrients with the standard deviation of RYA being two to three times lower than for unfertilized plots. The omission of nitrogen and potassium was associated with a decrease in yield stability and a decrease in the number of simultaneous positive and negative yield anomalies among treatments. Especially in root crops nutrient supply strongly influenced both annual yield anomalies and changes in anomalies over time. During the second half of the observation period yield stability decreased for sugar beet and increased for winter wheat. Potato yields were more stable during the second period, but only under complete nutrient supply. The critical role of potassium supply for yield stability suggests potential links to changes in the water balance during the last decades. Results demonstrate the need to explicitly consider the response of crops to long-term nutrient supply for understanding and predicting changes in yield stability.

1. Introduction

In face of climate change and an increasing global population, research on the stability of crop yields and their response to environmental perturbations is of critical importance. The long-term variability of crop yields is largely determined by the variability of meteorological conditions (Lobell and Field 2007, Ray *et al* 2015, Frieler *et al* 2017). However, weather-induced variability of crop yields can be affected by crop fertilization management (Berzsenyi *et al* 2000, Hao *et al* 2007, Mallory and Porter 2007, Ma *et al* 2012, Macholdt *et al* 2019). For a realistic assessment of such effects they have to be observed at representative time scales (at least decades) (Hejcman *et al* 2012). This perspective can be provided by long-term agricultural experiments where factors such as fertilizer supply, crop species and rotation are kept constant over several decades (Rasmussen *et al* 1998). Such experiments are rare. Consequently, little quantitative information is available on the long-term (50+ years) impact of nutrient supply on yield stability (Li *et al* 2019).

For crops cultivated in central Europe, both, decreases and increases in yield stability over the last decades have been reported (Calderini and Slafer 1998, Chloupek *et al* 2004, Osborne and Wheeler 2013, Iizumi and Ramankutty 2016, Döring and Reckling 2018, Schauberger *et al* 2018, Bacsi and Hollósy 2019, Agnolucci and De Lipsis 2020, Hadasch *et al* 2020). Discrepancies are related to differences in study period, location and crop but might also result from site-specific management adaptations, such as sowing date and fertilization management. The analysis of observations from long-term fertilization experiments might shed light on the effect of such factors.

Here we analyse the relation between long-term nutrient supply and yield stability for four major European crops (winter wheat, winter rye, potato and sugar beet). Crops were grown in a rotation (parallel growth of all crops in each year) at the Dikopshof long-term fertilization experiment (1955–2008, Germany) (Rueda-Ayala *et al* 2018). We analysed data from six treatments supplied with relatively low amounts of mineral nitrogen (N) fertilizers (maximum supply of 230 kg N h^{-1} to each crop within a typical 5 year crop rotation). Treatments ranged from complete fertilization over the omission of individual nutrients (N, phosphorus (P), potassium (K) or calcium (Ca)) to zero fertilization. We aimed to answer the following research questions: (a) Was crop yield stability affected by long-term nutrient omission and which nutrients were critical for yield stability? (b) Did such effects differ among crop species? (c) How did yield stability change over time (1955–2008)?

2. Material and methods

2.1. Research site and selected fertilization treatments

The Dikopshof long-term fertilization experiment was established in 1904 in Western Germany near Cologne. The soil type is a Chromic Luvisol (Rueda-Ayala *et al* 2018). It was developed from a >100 cm loess layer over a sandy-gravelly, highly permeable pleistocene middle terrace of the Rhine river. The arable layer has a loamy silt texture with a thickness of around 35 cm. The Atlantic climate with mild winters and summer has mean annual temperature of 10.3 °C and a mean annual precipitation of 693 mm (1955–2008, source: German Meteorological Service) (Zhao *et al* 2015). During the observation period a 5 year crop rotation typical for the region was maintained with (in the following order) Persian clover (*Trifolium resupinatum* L.), potato (*Solanum tuberosum* L.), sugar beet (*Beta vulgaris*), winter wheat (*Triticum aestivum* L.) and winter rye (*Secale cereale* L.). Each crop was grown in 24 fertilizer treatments (Rueda-Ayala *et al* 2018). The experimental design was not randomized. For each crop × treatment combination there is only one replicate (one observation) in each year. The five crops were grown in parallel, resulting in a total number of 120 plots, with a plot size of 18.5 × 15 m (supplementary figure S1 (available online at https://stacks.iop.org/ERL/16/014003/mmedia)). After harvest, potato leaves and stubbles of cereals were left standing until the beginning of October, when they were incorporated into the soil during tillage, whereas sugar beet leaves and clover cuttings were removed. Crops were grown under conventional management practice. Growth regulators, herbicides, and crop protection (fungicides and pesticides) were applied starting from late 1950s and early 1960s, respectively. In 1964 the ploughing depth was increased from 22 to 30 cm due to agricultural mechanization.

Table 1. Total amounts (kg ha^{-1}) of nutrients (N = nitrogen, P = phosphorus, K = potassium, Ca = calcium) supplied within the complete 5 year crop rotation for the different treatments. See supplementary table S1 for crop yield statistics.

Treatment	Elements (N-P-K-Ca)	Description
–NPKCa	0-0-0-0	No fertilization
–N	0-155-580-1143	No N
–P	230-0-580-1143	No P
–K	230-155-0-1143	No K
–Ca	230-155-580-0	No Ca
+NPKCa	230-155-580-1143	Complete fertilization

Yield data of potato and sugar beet (fresh weight), winter wheat and winter rye (14% moisture content) for the period 1955–2008 are reported as t ha^{-1} (figure 1, supplementary table S1). We analysed data from 6 out of 24 treatments where nutrient supply was kept constant for all crops since 1953. The six selected treatments were fertilized with synthetic (mineral) fertilizers only. Plots had either received all major macronutrients (complete fertilization), did not receive nitrogen (–N), phosphorus (–P), potassium (–K) or calcium (–Ca) or had not received any fertilizer (–NPKCa) (table 1). Data from 1975, 1998 and 1999 were excluded from the analysis due to a technical failure in harvest within one treatment (1998) and exceptional sowing of spring cereals (1975, 1999) instead of the typical winter-cereals sown in fall of the previous years.

2.2. Calculation of relative yield anomalies

For obtaining yield anomalies, data trends, which are considered as long-term changes in yield levels due to the combined effect of improved technology, agronomic management, and breeding, have to be removed. To account for curvilinear trends and non-stationarity we applied the locally weighted polynomial regression function to derive yield trends (T) (figure 1). Yields (Y) were normalized by the corresponding trend value (T), representing the expected

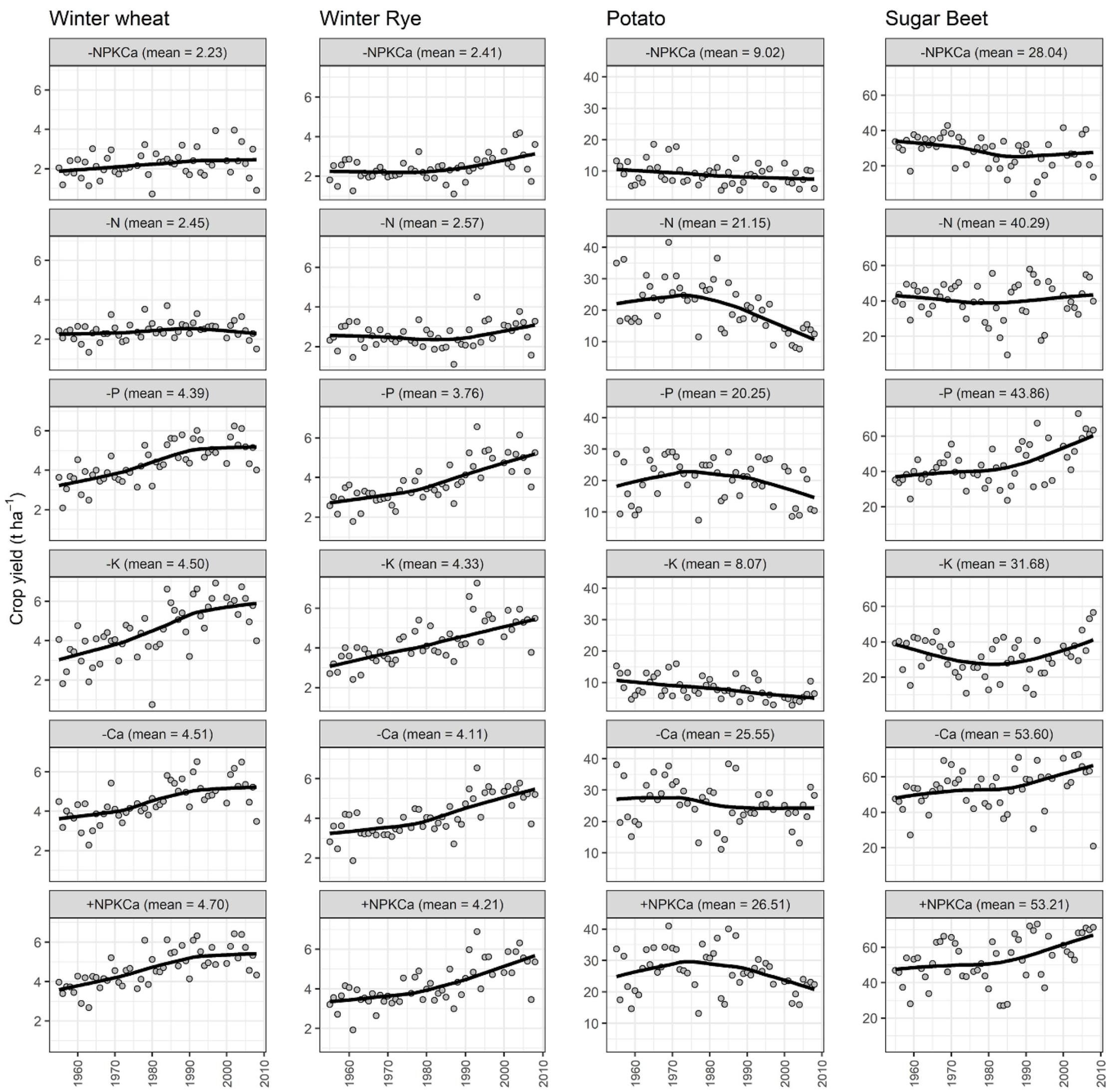

Figure 1. Absolute crop yields (t ha^{-1}) observed at the long-term fertilization experiment Dikopshof between 1955 and 2008 for four different crops and six fertilization treatments (cf table 1). Local polynomial regression trends are shown. Mean observed yield (t ha^{-1}) is given in brackets.

yield value in each year (index t) to obtain relative yields (Y_r) (Lu *et al* 2017):

$$Y_r = \frac{Y_t}{T_t} \quad (1)$$

By subtracting 1 from each data point resulting anomalies indicate the relative deviation of yields from the expected annual yield in each year (with the latter being described by the trend).

$$RYA = Y_r - 1 \quad (2)$$

Resulting relative yield anomalies (RYA) allow for a direct comparison of data obtained for different crops and within different treatments (figure 2).

2.3. Yield stability and changes over time

Yield stability was assessed using (a) the interquartile range of the RYA, (b) the standard deviation of the RYA, (c) first order lower partial moments (LPM) and (d) the relative frequency of negative, normal and positive yield anomalies. LPM are frequently used in agricultural economics (Antle 2010) to describe the shortfall risk below a specific threshold (k). We computed the first order LPM which describes the conditional expected value of shortfalls (accounting for the probability and magnitude of shortfalls). As a threshold we considered negative RYA deviating >15% from the expected (trend) yield value ($k = -0.15$). Results were affected by the value selected for k (with values ranging from -0.10 to -0.30 having been tested), but the overall pattern did not change. We further computed relative frequencies of normal years (anomalies within ±15% from the expected yields value) and positive/negative yield anomalies (>15% above/below the expected yield value, respectively). Stability measures were calculated for the data from the complete, the first (period 1: 1955–1981) and the second half (period 2: 1982–2008) of the study period. To further assess

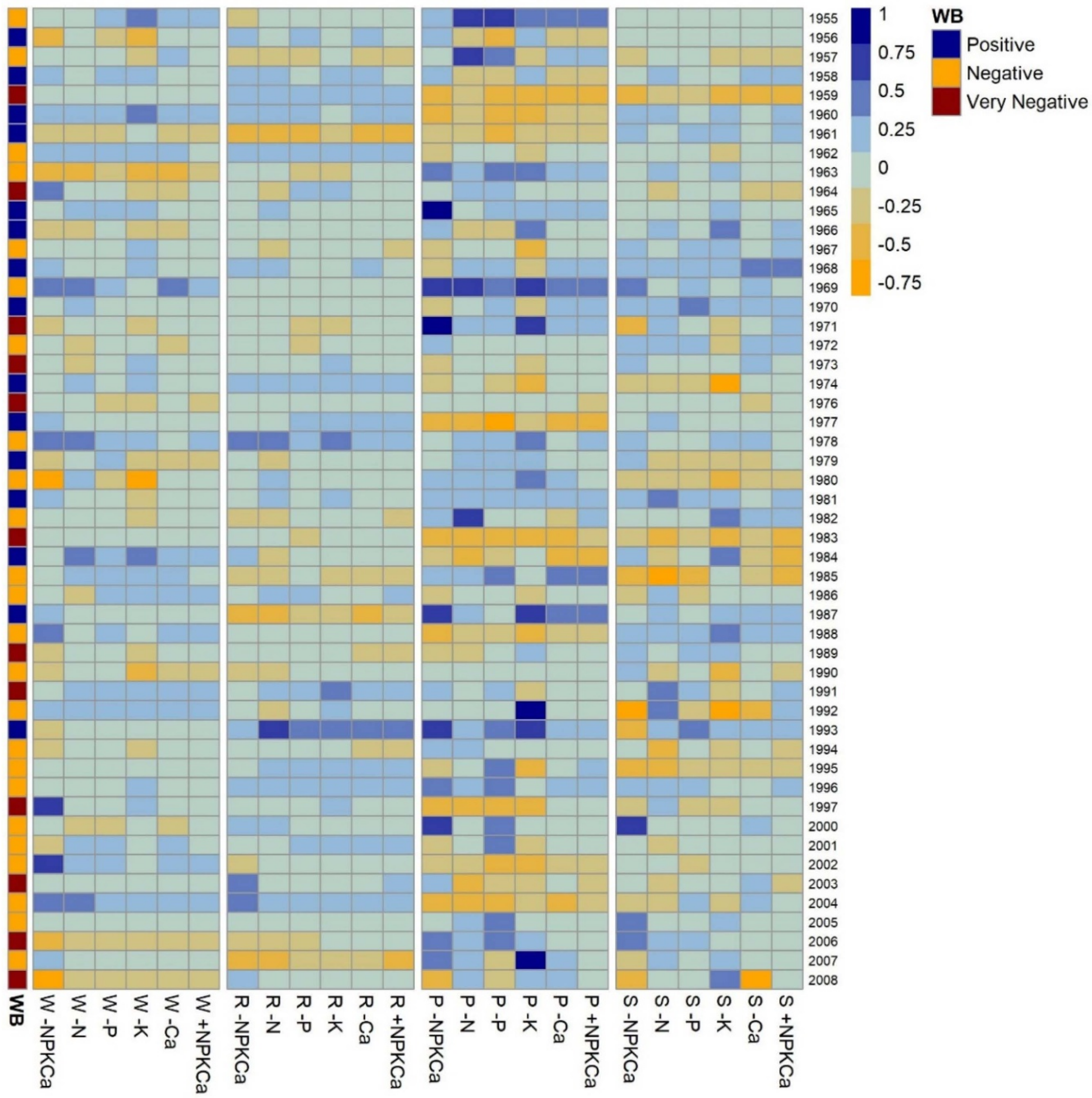

Figure 2. Heat map of the annual relative yield anomalies observed at the long-term fertilization experiment Dikopshof (1955 and 2008) for four different crops and six fertilization treatments (cf table 1). W = winter wheat, R = winter rye, P = potato, S = sugar beet. WB = Annual water balance (mm) calculated as the difference between annual sums of the reference evapotranspiration (Penman–Monteith equation) and precipitation (Positive: WB > −150, Negative: −150 > WB < 0, Very Negative: WB ≤ −150).

changes in yield anomalies and meteorological data over time we tested for the presence of monotonic trends using the non-parametric Mann Kendall test (Mann 1945). For RYA the absolute (non-negative) data values were used. Significant trends ($p \leq 0.05$) were quantified using the non-parametric Sen's slope estimator (Sen 1968).

2.4. Meteorological data

Meteorological data were obtained from the German Meteorological Service (http://www.dwd.de) and interpolated to a 1 × 1 km grid. The reference evapotranspiration (ET0) was calculated using the Penman–Monteith equation. For further details on interpolation and calculation approaches we here refer to (Zhao *et al* 2015). Daily data were aggregated to annual means and sums. The water balance (WB) was calculated as difference between annual ET0 and precipitation sums (in mm). While it was beyond the scope of the study to quantify the contribution of meteorological variability to yield stability, data were used as complementary information.

2.5. Association between yield anomalies

The association between RYA across treatments is considered as an indicator for the impact of nutrient supply on the response of crop yield anomalies to interannual weather variability. Strong associations indicate that the effect of annual weather conditions dominated over the effect of differentiated nutrient supply. In contrast, a lower level of association suggests that additional effects, such as nutrient supply, affected crop yield responses. Of particular interest for our study are changes in the number of simultaneous positive and negative yield anomalies among treatments over time. Associations were therefore quantified using the non-parametric Goodman and Kruskal's gamma coefficient (γ) which is based on the normalized difference between discordant and concordant data pairs (Goodman and Kruskal 1954). The γ coefficient describes the difference between the probability of concordant observations and the probability of discordant observations. Thus, negative values indicate a negative and positive values a positive association. Perfect positive and negative association are given at $\gamma = +1$ and $\gamma = -1$, while a value of 0 reflects no association at all.

All analyses were performed using the R statistical software version 4.0.2 (R Core Team 2020).

3. Results

3.1. Crop- and treatment-specific yield anomalies

For winter wheat the interquartile range of the RYA was highest if grown on unfertilized plots (figure 3(a)). For potato and sugar beet and for rye it was highest on soils that haven not received K or N fertilizer, respectively (figures 3(c) and (d)). For a given treatment, the interquartile range of potato yield anomalies systematically exceeded those of all other crops. Winter rye yield anomalies were least affected by differences in nutrient supply (figure 3(b)).

3.2. *Effect of fertilization treatment on yield stability (1955–2008)*

The standard deviation of potato and sugar beet yield anomalies exceeded that of cereals across treatments (figure 4(a)). The stability of rye was rather similar across treatments with slightly lower stability if grown on unfertilized soils or those where N supply has been omitted (figure 4(a)). Wheat, potato and sugar beet yields were least stable on zero fertilization and under K omission. Ca omission had a low effect on yield stability.

The conditional expected value of yield shortfalls (with $k = -0.15$) for wheat and sugar beet (figure 4(b)) agreed with the standard deviation of the RYA (figure 4(a)): it was highest under no fertilization, followed by K omission. For rye it was highest in unfertilized plots and those where Ca was not supplied. For potato crops conditional expected values of shortfalls were rather similar across treatments. They were on average higher than for the two winter cereals.

All crops, except rye, showed a higher relative frequency of negative yield anomalies if grown under long-term omission of K or under no fertilization (supplementary figure S2). Correspondingly, the frequency of normal years ($-0.15 > \text{RYA} < 0.15$) was lower under these treatments and highest under complete fertilization or if only Ca had been omitted. For wheat and sugar beet frequencies of positive were similar to those of negative anomalies (supplementary figure S2). This implies that an increase in normal yield anomalies (higher stability) was related to a decrease in both, positive and negative anomalies.

3.3. Changes in crop yield stability over time

For winter wheat the standard deviation of yield anomalies as well as the conditional expected value of shortfalls mostly indicated an increase or no changes in yield stability during the observation period (figures 4(a) and (b)). Yields in plots that did not receive K fertilizer (standard deviation and LPM) and the plots without P fertilizer (only LPM) were more stable during the second half (period 2) of the observation period (figure 4). The lower risk of yield failures was supported by an increased frequency of normal yield anomalies and a decreased frequency of negative yield anomalies (supplementary figure S2). Correspondingly, on the K omission plot we estimated a significant negative trend of absolute RYA values (slope: -0.002, p-value: 0.014).

For rye grown under N omission (–NPKCa and –N treatments), yield stability was slightly decreased in the second period (figure 4(a)). This is linked to a slight decrease in normal anomalies (supplementary figure S2). However, the expected value of shortfalls under Ca omission and no fertilization was decreased.

If grown in plots having received all nutrients, potato yield stability increased over time. This is indicated by a decreasing trend in RYA values (slope: -0.003, p-value 0.012), a lower standard deviation of RYA (figure 4(a)) and a higher frequency of normal yield anomalies (supplementary figure S2). However, both, frequencies of negative and positive yield anomalies were decreased. On Ca or K omission plots the frequency of normal years in period 2 was increased as well. However, this was rather linked to a decrease in positive yield anomalies (supplementary figure S2) and an increase in the standard deviation (figure 4(a)). If unfertilized, potato yield stability was higher during period 1. On such plots the frequency of both positive and negative yield anomalies were increased during the second half of the observation period (supplementary figure S2).

For sugar beet the standard deviation of RYA was higher during the second period across treatments except for complete fertilization and K omission where changes were small (figure 4(a)). The frequency of negative yield anomalies and normal years was increased and decreased in period 2, respectively, for almost all treatments (supplementary figure S2). The frequency of positive yield anomalies remained nearly unchanged. If unfertilized, sugar beet showed a significant upward trend of RYA values (slope: 0.007, p-value: 0.019).

Patterns of the standard deviation of RYA are similar to those of the coefficient of variation of absolute yield values (supplementary figure S3). Thus, the overall effects of differentiated nutrient supply

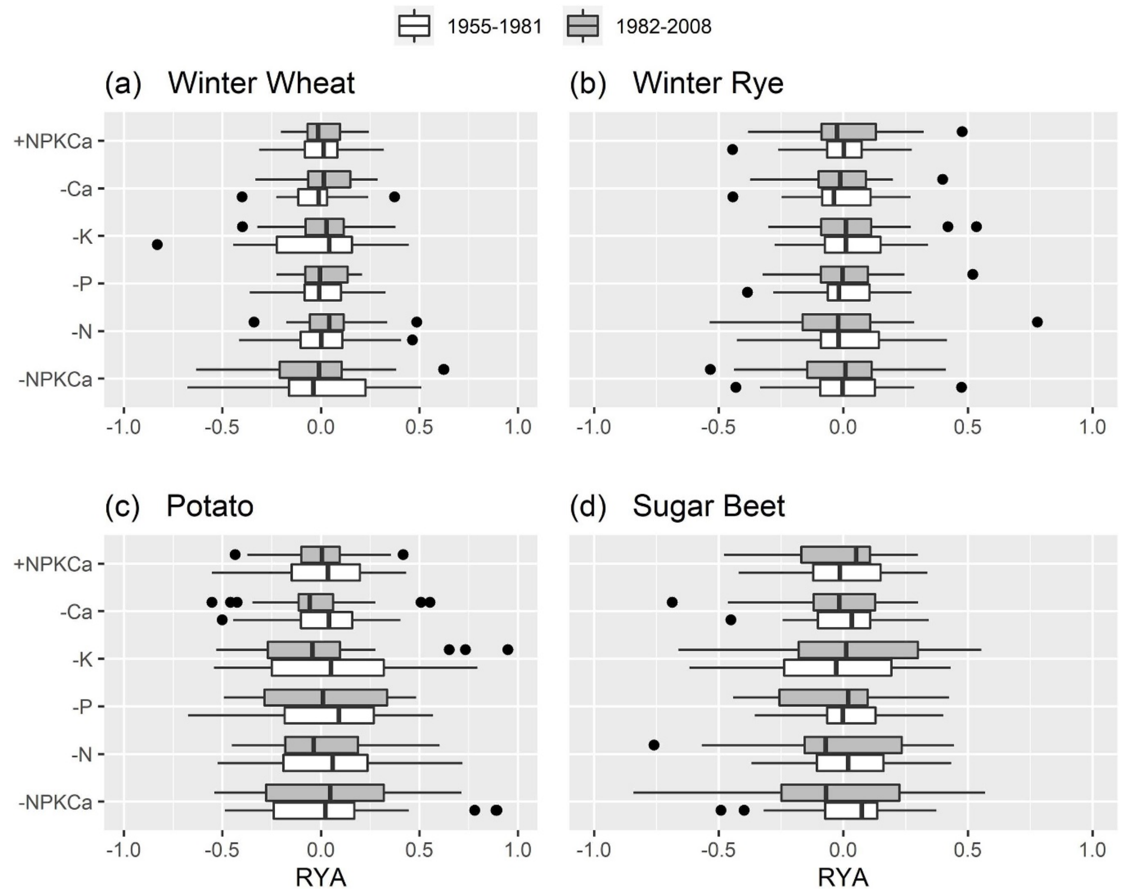

Figure 3. Boxplot of relative yield anomalies (RYA) of crop yields for winter wheat (a), winter rye (b), potato (c) and sugar beet (d) obtained at the Dikopshof site between 1955 and 1981 (period 1) and between 1982 and 2008 (period 2) in each treatment (cf table 1). Lower and upper values of the hinges (grey) correspond to the 25th and 75th percentiles, black vertical lines indicate median values and black dots indicate outliers which are defined as values beyond the range of the horizontal whiskers (up to 1.5× interquartile range).

are independent of whether absolute or relative yield anomalies are considered..

3.4. Association of yield anomalies

The association of yield anomalies across treatments was higher for cereals than for row crops (figure 5). At least 37% (for wheat) and 40% (rye) of the observation years yield anomalies were related to each other (concordant observations: positive or negative yield anomalies in both treatments). Higher proportions of ranked pairs in agreement indicate a more similar response of treatments to weather conditions across years. This suggests that weather-induced anomalies of cereals were less affected by nutrient omission (treatment) than those of row crops. For wheat and sugar beet grown under complete fertilization associations were lowest with the −NPKCa, followed by the −K treatment (figures 5(a) and (d)). For completely fertilized potato relations were lowest with the −K (figure 5(c)), followed by the −NPKCa treatment while for rye they were lowest with −NPKCa and −N omission plots (figure 5(b)). Thus, except for rye, the omission of K in particular led to a decrease in the association with anomalies observed under complete fertilization.

4. Discussion

4.1. Differences in yield stability between crops

Across treatments, yield stability was highest for winter rye, followed by winter wheat and sugar beet and was lowest for potato. The higher long-term stability of cereal yields compared with that of root crops agrees with results from other long-term experiments in Europe (Chloupek *et al* 2004). Especially winter cereals benefit from their long growing season. If soil water is replenished due to sufficient winter precipitation, early leaf and root growth allows them to use water more efficiently than spring-sown crops (Gan *et al* 2000). For spring-sown crops, such as potato and sugar beet, timing is more critical. Periods with unfavourable weather conditions and lower tuber growth cannot be compensated. This is especially true for potato crops, which have a shallow root system. The root density of sugar beet crops in deeper layers exceeds that of potato plants (Willigen and Noordwijk 1987). Thus, they are less vulnerable to seasonal fluctuations in growing conditions and their yields are more stable. In this context it is important to point out that cereal yields were reported as dry matter while for row crops yields were only available

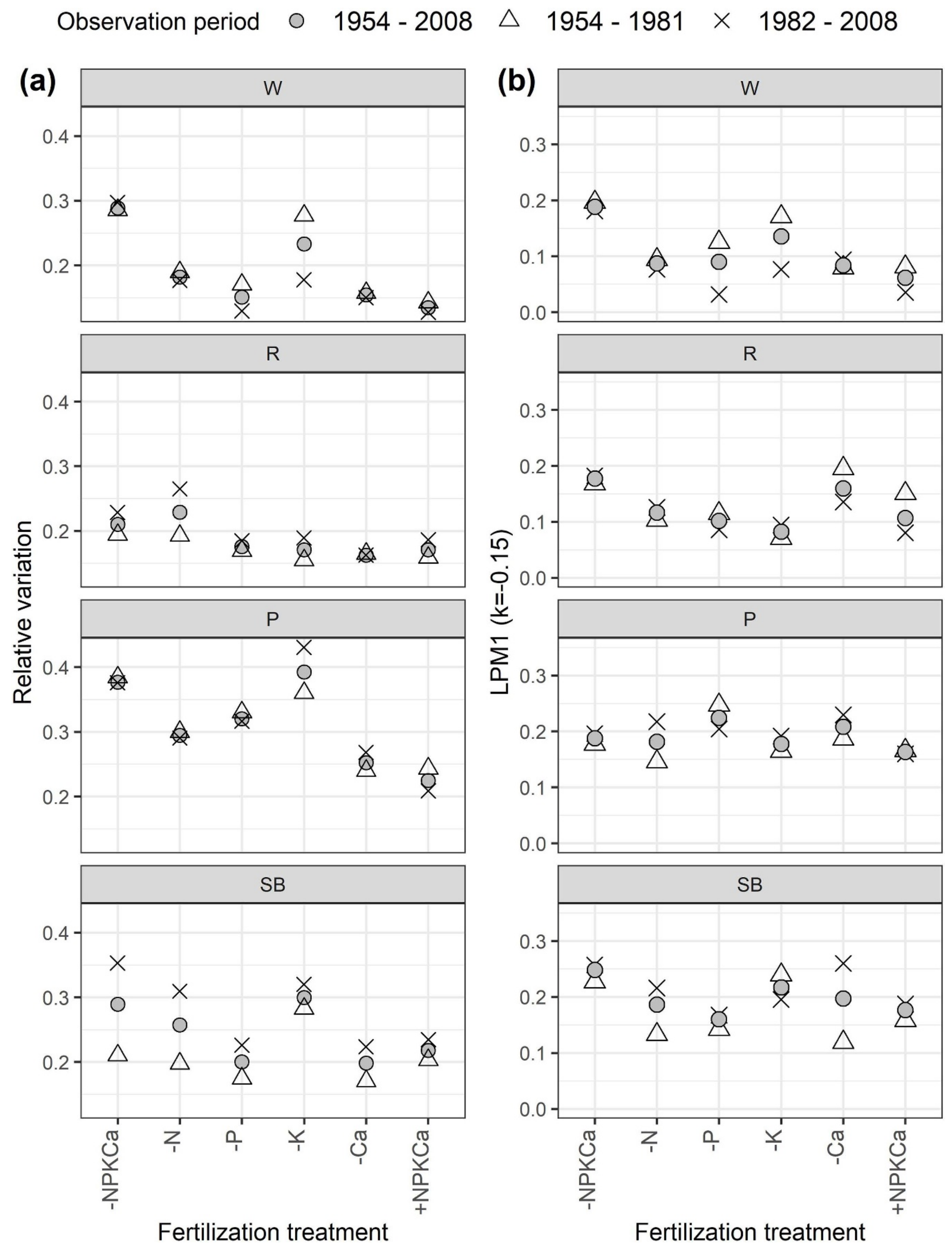

Figure 4. (a) Standard deviation of RYA (low values indicate high yield stability) and (b) first order lower partial moments (LPM, low values indicate high yield stability) with $k = -0.15$ at the Dikopshof site for each crop-treatment combination. Estimates for the complete (1955–2008) and subsets of the observation period are shown. W = winter wheat, R = winter rye, P = potato, SB = sugar beet.

as fresh matter. This might have amplified differences in yield stability between crops. The higher stability of cereals was accompanied by a higher fraction of concordant data pairs across treatments – compared with those of row crops (figure 5). These stronger associations indicate a similar response of crops to annual weather conditions (positive or negative anomalies were observed across treatments). Thus, for cereals differences in nutrient supply were less critical for leading to either positive or negative anomalies than for row crops.

4.2. Differences in stability between treatments

Highest yield stability was observed in plots receiving all nutrients (+NPKCa). Under no fertilization standard deviations of the RYA were two to three times

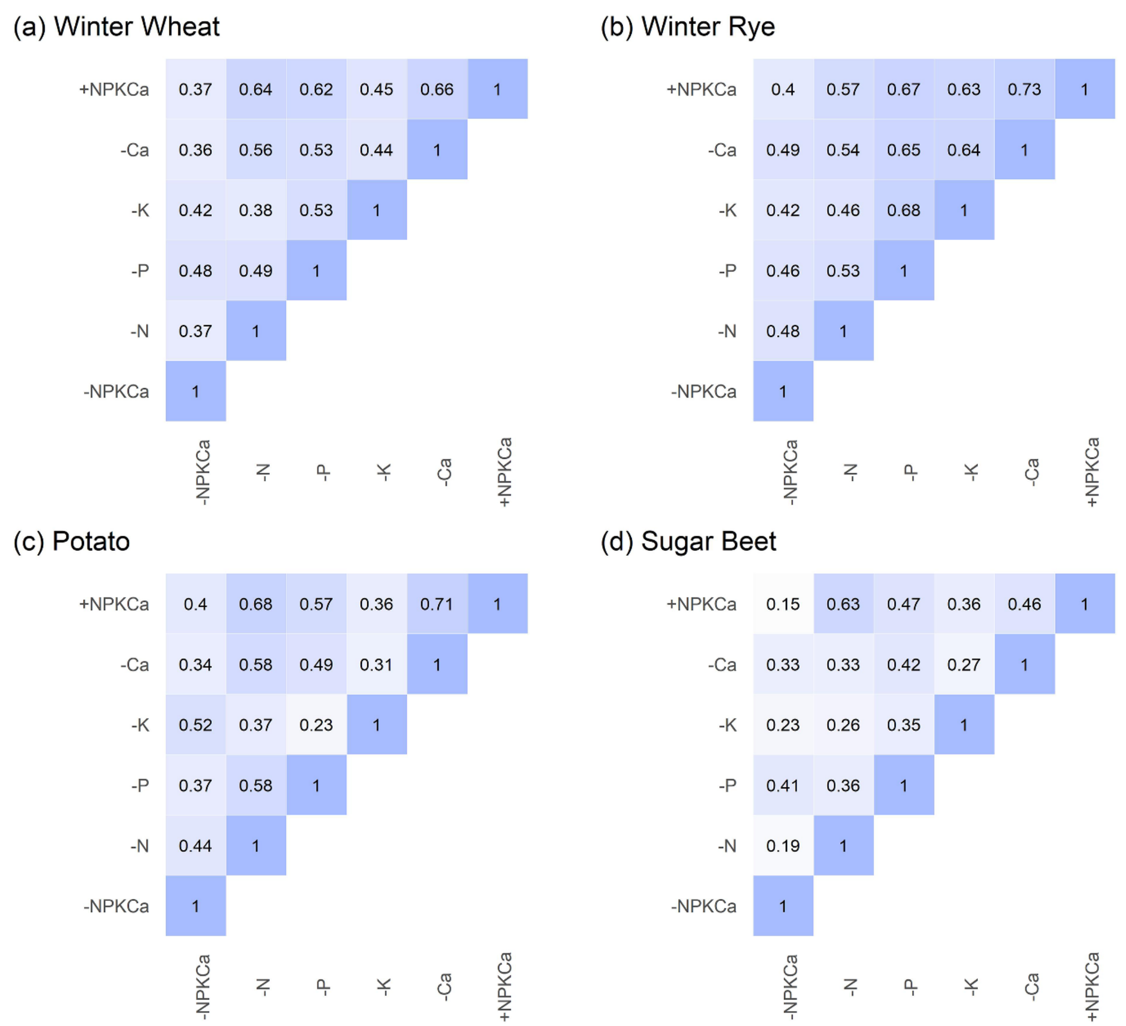

Figure 5. Goodman and Kruskal's gamma coefficient (γ) values calculated for the relative yield anomalies (RYA) observed in six different fertilization treatments (cf table 1) at the long-term fertilization experiment Dikopshof (1955 and 2008) for winter wheat (a), winter rye (b), potato (c) and sugar beet (d). High values indicate strong associations between treatment-specific RYA values (high number of concordant data pairs across years with positive or negative yield anomalies being observed in both treatments).

higher than for complete fertilization plots (except for winter rye). Omitting N (for rye) or K (for all other crops) supply was the key factor for decreasing yield stability. These patterns were independent from data processing and also visible in the absolute yield data (supplementary figure S3). Adequate N supply that matches the demand for a crop rotation in an integrated system (Spiertz 2010) has also been reported as a critical factor for yield stabilization in other studies (Berzsenyi *et al* 2000, Varvel 2000, Hao *et al* 2007, Macholdt *et al* 2019). It promotes plant growth, rooting depth and density and thus, modulates soil characteristics and enhances plant resilience to adverse growing conditions. K supply mainly affects the water use efficiency of crops and is especially critical under growing conditions with frequent occurrence of drought stress periods (Grzebisz *et al* 2013, Zörb *et al* 2014). Low yield stability on K omission plots therefore suggests that the amount of crop available water was one of the main factors affecting yield stability at our site. Findings highlight the critical role of K supply for a sustainable crop production under rainfed conditions. They further suggest investigating the relation between water availability and yield stability at our site. While the mean annual WB (indicated in figure 2) cannot capture complex interactions at the field scale, the use of process-based models might help understanding moisture effects related to yield stability. Low yield stability on unfertilized plots might be related to sparse vegetation cover and therefore high soil evaporation losses. In addition, due to a poorer soil quality, they are more susceptible to waterlogging than those plots receiving more nutrients. Nutrient supply further affected the association strength between treatment-specific yield anomalies (figure 5). Anomalies observed under complete fertilization were least strongly related to those of unfertilized treatments. Thus, long-term nutrient omission strongly decreased the probability that crops respond similarly to weather conditions than crops grown under complete fertilization (positive or negative yield anomaly in both treatments). The omission of K was the most (for potato) or second most (for winter wheat and sugar beet) important factor for reducing associations. Since yields were most stable in the +NPKCa treatment these results provide further evidence on the critical role of K supply for stabilizing yields under changing weather conditions at our site.

4.3. Changes over time

Yield anomalies are largely controlled by changes in meteorological conditions (Moore and Lobell 2015, Ray *et al* 2015). In the 1980s a major regime shift has been observed leading to changes in meteorological conditions over Europe, such as increased temperatures (Reid *et al* 2016). In accordance with this, air temperature, radiation and ET0 sums significantly increased over time at our site (supplementary table S2). Trends suggest that under rain-fed cultivation conditions, as in this study, water availability had decreased over time. Correspondingly, the number of years with a negative WB (based on the ET0) was higher in the second half of the observation period (22 in period 2 versus 14 in period 1) and the number of years with a positive WB lower (12 in period 1 versus 3 in period 2) (figure 2). Sugar beet yields are largely controlled by water supply (Hoffmann and Kenter 2018). Thus, increased evapotranspiration rates and a decrease in soil water availability during the last decades might have contributed to the lower stability (despite a prolonged growing season). This was reflected in higher standard deviation of sugar beet yield anomalies (in N omission and unfertilized plots, figure 4(a)) and higher probability of sugar beet yield failure (N and Ca omission in figure 4(b)) in the second half of the observation period. We further observed a strong decrease in the association of yield anomalies among treatments in period 2 (supplementary figure S4(d)). Thus, the long-term omission of nutrients strongly reduced the probability, that plants grown in the different treatment plots respond similar to changing weather conditions (positive or negative yield anomalies across treatments). However, with full fertilizer application, sugar beet yield anomalies tended to be low and were rather constant over time (figures 3(d) and 4). When receiving all nutrients, the stability of potato yields was higher after 1981 (lower frequencies of positive and negative anomalies in supplementary figure S2 and the negative Sen's slope). However, it tended to be lower if plants were grown on plots where K was omitted (slightly increasing standard deviation in period 2 in figure 4 and lower frequency of normal years in period 2 in supplementary figure S2). Considering the importance of K fertilization under dry field conditions (Grzebisz *et al* 2013, Zörb *et al* 2014), the destabilizing effect of omitting K on potato yields in period 2 was thus probably related to a decrease in water availability over time. As for sugar beet, the fraction of concordant data pairs (positive or negative yield anomalies in treatment data pairs) was lower in period 2 (supplementary figure S4(c)). Thus, fertilization did not only affect potato yield anomalies in single years (figure 2) but also led to a contrasting response of crop yields to meteorological fluctuations over longer-term time scales. Contrasting with the findings for potato, the stability of wheat yields in K omission plots increased over time (negative trend of yield anomalies). The development of short-straw cultivars (being less susceptible to lodging) and the progress in agronomic management (e.g. plant protection and growth regulators) might have led to a lower dependency of wheat yield anomalies on K supply under adverse weather conditions. The lower dependency consequently led to stronger associations between anomalies under complete nutrient supply with those of the −K treatment during period 2 (1982−2008) (supplementary figure S4(a)).

4.4. Limitations of the study

On a longer-term time scale crop yields are influenced by changes in agricultural management (e.g. technology, fertilizer management and properties, management dates, crop protection, seed treatment) and crop varieties. These factors could not be kept constant over time and affected yield stability. Application of chemical crop protection strongly increased from the early 1960s to the 1990s. Research trials such as our site were subject to continuous observations. Nevertheless, chemical crop protection probably contributed significantly to a lower risk of yield loss. This is especially true for treatments receiving higher amounts of nutrients which are characterized by denser canopies with microclimates favourable for fungal infection and the spread of diseases (Tivoli *et al* 2013). Thus, crop protection might have contributed to the increase in yield stability of treatments receiving more nutrients over time (i.e. for potato in figure 4 and indicated by the negative trend in RYA). At our site, the cumulative effect of nutrient omission affected soil properties, such as pH-value and content of soil organic carbon. The water holding capacity of all treatments might have benefitted from an increase in the ploughing depth in the mid-1960s. Further, crop rotational effects (i.e. with respect to the nutrient availability after harvesting the preceding crop and the nitrogen fixation of clover) must be considered. We did not account for cultivar-specific traits, such as phenology (Rezaei *et al* 2018) and root characteristics (Li *et al* 2016). These traits might affect crop responses to fertilization (Addy *et al* 2020) and their adaptation capacity to variable environmental conditions (Blum *et al* 1989, De Vita *et al* 2010). Exemplarily, drought stress tolerance of potato cultivars was researched much later than that of cereals (Monneveux *et al* 2013). The selection for drought tolerance was less critical in countries where water shortage has not been an issue in the past or where potato is frequently irrigated, such as Germany. Therefore, more detailed studies are required to confirm and explain the patterns and trends in yield anomalies that we observed.

It was beyond the scope of this study to attempt a detailed mechanistic explanation for the yield stability observed at the Dikopshof long-term fertilization experiment. The interaction between genotype, management, and environment creates a high level of complexity (Lobell and Gourdji 2012) and crop yield responses to weather conditions strongly vary with crop phenological stage. Due to the high number of confounding factors statistical relations between weather and yield data and yield anomalies cannot be used for assessing causal relationships (Siebert *et al* 2017). Process-based crop models that allow for varying one input factor at a time, while keeping all others fixed, are required for separating weather effects from those of other factors. However, pronounced differences in yield stability and association between treatments illustrate that stability was strongly affected by the supply of nutrients, in especial by the omission of nitrogen and potassium (research question (1)). These effects differed between crops and were strongest for row crops and lowest for winter rye (research question (2)). Stability changed over time, but the statistical significance and the direction of trends differed between crop × treatment combinations and cannot be generalized (research question (3)). Our understanding of management effects on past and future yield stability will benefit from investigations across similar long-term experiments.

5. Conclusions

Long-term fertilization experiments, such as the Dikopshof (Germany), provide unique data for studying the long-term response of yield stability to nutrient supply. The long-term nutrient supply strongly affects the yield stability of winter rye, winter wheat, potato and sugar beet, which are major European food crops. Stability can be greatly enhanced by balanced fertilization with all major macronutrients. Assessments of yield stability therefore need to account, in addition to climate variability, also for changes in nutrient supply. The critical role of potassium supply at our site suggests that changes in the WB during the last decades might deserve a more in-depth investigation in future studies. Trends in yield stability over time strongly differ between crop × treatment combinations and cannot be generalized. Knowledge on the long-term nutrient supply is critical for understanding and predicting changes in crop yield stability.

Data availability statement

The data that support the findings of this study are openly available at the following DOI: https://doi.org/10.20387/bonares-Y8A0-2Z3F.

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