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Impact of nutrient supply on the expression of genetic improvements of cereals and row crops – A case study using data from a long-term fertilization experiment in Germany

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ABSTRACT

Impacts of nutrient supply and different cultivars (genotypes) on actual yield levels have been studied before, but the long-term response of yield trends is hardly known. We present the effects of 24 different fertilizer treatments on long-term yield trends (1953–2009) of winter wheat, winter rye, sugar beet and potato, with improved cultivars changing gradually over time. Data was obtained from the crop rotation within the long-term fertilization experiment at Dikopshof, Germany. Yield trends were derived as the slope regression estimates between adjusted yield means and polynomials of the first year of cultivation of each tested cultivar, when tested for more than two years. A linear trend fitted best all data and crops. Yields in highly fertilized treatments increased linearly, exceeding $0.08\,\mathrm{t\,ha^{-1}\,a^{-1}}$ for both, winter wheat and winter rye, and ≥ 0.30 and $\geq 0.20\,\mathrm{t\,ha^{-1}\,a^{-1}}$ for sugar beet and potato fresh matter yields. Yield trends of winter cereals and sugar beet increased over time at N rates $\geq 40\,\mathrm{kg\,ha^{-1}\,a^{-1}}$, being 0.04–$0.10\,\mathrm{t\,ha^{-1}\,a^{-1}}$ for cereals and 0.26–$0.34\,\mathrm{t\,ha^{-1}\,a^{-1}}$ for sugar beet, although N rates $> 80\,\mathrm{kg\,ha^{-1}\,a^{-1}}$ produced a stronger effect. Nitrogen was the most influential nutrient for realisation of the genetic yield potential. Additional supply of P and K had an effect on yield trends for rye and sugar beet, when N fertilization was also sufficient; high K rates benefited potato yield trends. We highlight the importance of adequate nutrient supply for maintaining yield progress to actually achieve the crop genetic yield potentials. The explicit consideration of the interaction between crop fertilization and genetic progress on a long-term basis is critical for understanding past and projecting future yield trends. Long-term fertilization experiments provide a suitable data source for such studies.

1. Introduction

Globally averaged, crop yields have increased considerably in the last decades, by 56% between 1965 and 1985 and 20% between 1985 and 2005 (Foley et al., 2011). Positive yield trends are attributed to crop breeding progress, increased application of fertilizers and improved agronomic management. However, large differences between potential crop yield and actual farm yield (yield gaps) have been observed (Fischer, 2015). Therefore, it is crucial to understand the causes and trends of potential and actual crop yields, taking into account the growing global population, the crop and location-specific impact of climate change, the biological limits to yield and the regionally observed leveling-off or decrease of farm yields (Olesen et al., 2011; Peltonen-Sainio et al., 2016; Ray et al., 2013).

Actual crop yields are strongly determined by the specific cultivar (genotype), the environment, the nutrient supply (management) and the interaction among these factors (Simmonds, 1981; Sattelmacher et al., 1994). Complex synergistic and antagonistic relationships between nutrients supplied by synthetic or organic fertilizers, and their effects on actual and potential yields have been documented and employed for deriving site- and crop-specific fertilization strategies. Simultaneously, progress in plant breeding has provided genotypes with improved quantitative and qualitative yield traits, such as high yielding cereal varieties of increased nutrient demand, but better responsive to fertilization (Tilman et al., 2002). The importance of different soil fertility regimes for plant breeding and cultivar selection has been

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demonstrated (McDonald et al., 2015; Rengel and Damon, 2008; Stagnari et al., 2013; Wang et al., 2017). Understanding these interactions is critical for regions of nutrient deficient soils and limited access to fertilizers or where intensification of crop production has barely begun, as well as for highly productive agricultural areas requiring a balanced nutrient management for a sustainable crop production with reduced environmental impacts (Pradhan et al., 2015; West et al., 2014).

Effects of the interaction between genotypes and fertilization regime on long-term yield trends (> 50 years) are barely known, likely because suitable historical yield data sets for studying such effects are hardly available (Simmonds, 1981). Genetic and non-genetic crop yield trends have been described from well-managed variety trials (Laidig et al., 2014; Mackay et al., 2010; Piepho et al., 2014; Rijk et al., 2013). Those studies applied fertilization practices varying markedly across years and locations, and with cultivars tested for few years. Consequently, results might be unrealistic for long-term yield trends under non-optimal crop growth conditions. Furthermore, while yield trends have been mainly quantified for major cereals, only a few studies are available on long-term trends and interaction effects for minor crops of regional importance.

Long-term experiments (LTE) have been established worldwide to analyse long-term effects of nutrient deficiency and different fertilization strategies on soil fertility, plant growth and crop yield at field scale for periods > 20 years (Rasmussen et al., 1998; Berti et al., 2016). Contrasting to farm conditions, LTE treatments and agronomic management practices remain unchanged for many years, thus providing useful data for disentangling the different effects of variables in the complex matrix of factors affecting soil fertility and plant productivity (Körschens, 2006). LTE keep record of slow changes which cannot be tackled in the framework of short-term experiments, because of the confounding effects of other factors like climate variability. Previous LTE studies mainly focused on quantifying relative yield differences among fertilizer treatments (Ellmer et al., 2000; Kunzová and Hejcman, 2010; Mackay et al., 2010). Others concentrated on long-term differences in fertilization on soil properties, such as the content of soil organic matter (SOM) and biological activity or on the effects of different crop rotations on yield and soil properties (Christensen, 1997; Mercik et al., 1997; Kaiser et al., 2007; Heinze et al., 2010).

Up to now, studies on the long-term effects of different fertilizer regimes have been mainly restricted to comparing yield trends from fully fertilized plots or with different nitrogen levels against unfertilized plots. Edmeades (2003) analysed the effect of different fertilizer types on long-term yield trends, although comparing data from the latest possible 10–20 years, due to the unknown interaction between time and treatment. However, LTE have not been analysed yet to describe effects of the interactions among cultivar change, fertilizer application rate and fertilizer type on long-term yield trends. Considering the crop-specific shifts in breeding goals during the last decades, it is not clear whether these effects can be generalized across different crop species. Therefore, we present here an analysis of long-term yield trends (1953–2009) observed for winter wheat (*Triticum aestivum* L.), winter rye (*Secale cereale* L.), sugar beet (*Beta vulgaris* L.) and potato (*Solanum tuberosum* L.), grown in a crop rotation at the LTE Dikopshof near Cologne (Germany). Objectives were to test for significant differences in long-term yield trends caused by (i) fertilization rate of the specific crop nutrients nitrogen (N), phosphorus (P), potassium (K) and calcium (Ca); (ii) fertilizer type, distinguishing application of synthetic fertilizers, farmyard manure or both; and (iii) the genetic progress achieved for that period for the four specific crops.

2. Materials and methods

2.1. Study site and experimental design

The LTE Dikopshof was established on the Dikopshof experimental farm, in Western Germany near Cologne (50.8079 N, 6.9529 E, 62 m a.s.l.). The soil type refers to a Haplic (Chromic) Luvisol, developed from a nearly 100 cm loess layer over a sandy-stony, highly permeable pleistocene middle terrace of the river Rhine (Holz, 1983). The arable layer of loamy silt soil texture has a thickness of around 35 cm and groundwater is located at a depth of 19 m. The region is characterized by maritime climatic conditions with an average precipitation of 633 mm per year and an average air temperature of 10.0 °C (Dikopshof Meteorological Station, measurements 1950–2010).

The experiment was implemented by Hansen in 1904 (Hansen, 1908), with a design of complete blocks of fertilization and nutrient deficiency treatments per crop, but without replications (cf. Appendix Figure A1). Up to 1950, sugar beet (SB), winter wheat (WW), winter rye (WW), a forage crop and oat were cultivated in parallel, during a cropping cycle and then subsequently rotated; since 1950 potato (P) replaced oat (cf. Appendix Table A1). The forage crop was mainly Persian clover (*Trifolium resupinatum* L.) or occasionally Berseem clover (*Trifolium alexandrinum* L.). Since 1953, each crop was tested in 24 fertilizer treatments of variable application form (synthetic fertilizer or manure) and application rate of N, P, K and Ca (cf. Appendix Figure A1; Table A2). The experiment consisted of five blocks, each one containing one crop and 24 treatments arranged in 120 plots of the size 18.5 m × 15 m.

Since around 1951, sugar beet, winter rye and potato received supplementary fertilizer additions in organic form (farmyard manure), in mineral form, or as a combination of both, manure and synthetic fertilizer treatment (Table 1; Appendix Table A2). However, manure and mineral supplements were not randomly applied: half of the field received manure and half of each block received mineral supplements. Therefore, the 24 treatments could not be analysed as a factorial arrangement, but rather as single treatments (Richter and Kroschewski, 2006; Loughin et al., 2007; Plaia, 2015; Onofri et al., 2016). Winter wheat received fertilizer exclusively in synthetic form. Persian clover was not fertilized with synthetic N, but it received 1143 kg ha^{-1} a^{-1} of Ca and the same application rate of P and K than the other crops. From 1953 through 2009, the described fertilization regimes and crop rotation clover (C), potato (Pot), sugar beet (SB), winter wheat (WW), winter rye (WR) were maintained with five sequences, and these sequences were repeated in cycles every 5 years, as shown in Table 2, with term definitions according to Richter and Kroschewski (2006), Loughin et al. (2007), Plaia (2015), Onofri et al. (2016). Treatment ID 24 was not fertilized; however, the symbiotic N fixation by Persian clover included in the rotation contributed to the soil nitrogen content (Schellberg and Hüging, 1997). During the study period, different cultivars typical for the region were tested and gradually changed over the whole study period (Appendix Figure A2), independently of cycles.

2.2. Data acquisition and analysis

Crop yields (t ha^{-1}) of winter wheat, winter rye, sugar beet and potato recorded between 1953 and 2009 were analyzed. Yield records prior 1953 were excluded from the analysis, and only fertilizer treatments and crop rotation kept constant until 2009 were considered (cf. Appendix Table A1). Some records were missing, due to failures in harvesting of sugar beet in 1954 and a severe weed infestation in unfertilized plots (Table 1, ID 24) of all crops in 1998. Yield data was obtained for each fertilizer treatment and crop as dry matter for cereals and fresh matter for potato and sugar beet.

Because in LTEs different cultivars are grown over a variable number of years, yearly yield data of a same cultivar represent repeated measures during its testing period and account for interannual changes of meteorological conditions and management practices. Due to the lack of true replicates in this study, the single yield value per cultivar, fertilizer treatment and year was available. To determine yield trends over time, separately by crop, two steps were employed, after Rijk et al. (2013); the R code for data analyses is given in the Appendix. Firstly, to