Agriculture, Ecosystems and Environment 372 (2024) 109100

Contents lists available at ScienceDirect

Agriculture, Ecosystems and Environment

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

The impact of climate and potassium nutrition on crop yields: Insights from a 30-year Swiss long-term fertilization experiment

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ARTICLE INFO

Keywords:
Yield response
Climate change
Long-term field experiment
Soil potassium availability

ABSTRACT

Climate change will strongly influence agricultural practices in the future. In order to promote resource-efficient agriculture, it is important to analyse the impact of climate variation on crop yields. In this study, we report yields of spring wheat, winter barley, maize, potato and sugar beet from the long-term crop rotation and fertilization experiment Demo in Switzerland and analyze their response to different climate variables (e.g., annual and seasonal temperature, precipitation, evapotranspiration, number of heat days and days of heavy rainfall). In addition, we investigate the impact of readily plant-available soil potassium (K) on the relationship of crop yields and precipitation. Annual and summer temperatures increased by 1 °C and 1.5 °C, respectively, over the observation period, and both the number of heat days and days of heavy rainfall increased in summer. Rising summer temperatures have a negative impact on all crop yields, which was most prominent for spring wheat, potato and maize. Annual, spring and summer precipitation show varying effects on different crops. For maize, soil K has a mediating effect on yield reductions under low spring precipitation. Yields are significantly reduced by 1 t ha^{-1} per 100 mm reduction of precipitation below a soil K threshold of 7 mg K kg^{-1} soil. Based on these results and the future climate scenarios for Switzerland, crop rotations with less heat-sensitive species and early-maturing varieties should be considered. In order to keep future irrigation demands and costs as low as possible, the soil K fertility classes in the Swiss K fertilization guidelines might need to be revisited. Our study is one of a few long-term observations that show the impact of climate variation on crop yields and highlights the potential of K management as a climate change adaptation measure.

1. Introduction

Agricultural practice is strongly affected by climate as temperature, rainfall and radiation influence crop yields (Olesen and Bindi, 2002). Extreme events of these parameters like heat days, frost, heavy rainfall and drought typically have negative effects on yields (Olesen and Bindi, 2002; Thornton et al., 2014). With climate change, temperature will rise and extreme events become more likely (Zubler et al., 2014; Scherrer et al., 2016). Compared to the global land surface, Europe is predicted to warm approximately 1.6 times faster (van der Schrier et al., 2013) and Switzerland, located in Central Europe, will be even more affected. While the average annual temperature worldwide has been rising by 1.1°C since the pre-industrial reference period to date, in Switzerland, the increase has been about 2°C (FOEN et al., 2020). The reasons are the distance to the sea, which entails a higher specific heat capacity of the land, and the melting glaciers, which result in a lower albedo and thus a stronger warming (FOEN et al., 2020).

The agricultural area in Switzerland occupies roughly 1 M hectares, corresponding to 24 % of the total land area, and is primarily located in the Swiss lowland (Köllner, 2017). Arable farming is characterized by diverse crop rotations with a high share of fodder crops such as maize, barley and grass-clover ley (FOAG, 2022). Besides, the most important arable crops for human consumption are wheat, sugar beet and potato (FOAG, 2022). As C_3 plants, wheat, barley, sugar beet and potato have their temperature optimum at 20–25°C (Bonhomme, 2000) and their yields are expected to be negatively affected by rising temperatures (Hijmans, 2003; Hawkins et al., 2013). In contrast to these crops, maize is a C_4 crop with a considerably higher temperature optimum (Sánchez et al., 2014). The effect of increasing temperature on maize yields could therefore be even positive in Switzerland (Holzkämper et al., 2015). Summer precipitation may influence crop yields positively, due to its mediating effect on crop water stress and, with this, yield reductions

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https://doi.org/10.1016/j.agee.2024.109100
Received 23 December 2023; Received in revised form 22 May 2024; Accepted 24 May 2024

(Brunner et al., 2019). However, ample spring precipitation has often been associated with yield decreases due to increased pest infestation of winter crops (Büchi et al., 2019) or delayed sowing of summer crops (Urban et al., 2015).

In Switzerland, a shift in precipitation patterns is expected with higher rainfall in spring and lower rainfall in summer (Croci-Maspoli et al., 2018). As C_4 crops suffer more severely from drought stress than C_3 plants (Guidi et al., 2019) one can expect that maize is more susceptible to respond to decreasing summer precipitation with yield losses than other crops. Around 150–200 mm of irrigation water are currently used in Swiss maize production, accounting to roughly 2’000–2’500 CHF ha^{-1} (Zorn and Lips, 2016; Holzkaemper, 2020). These demands are projected to increase in the future (Holzkaemper, 2020), putting climate change increasingly in the focus of economic viability of agriculture. However, there are only few studies on the effects of climate and its individual variables on crop yields in Switzerland and most of them use crop-modelling approaches (Holzkämper et al., 2013, 2015; Rogger et al., 2021).

Besides genetic drivers of water use efficiency, potassium (K) nutrition plays an outstanding role in plant-water-relations (Tavakol et al., 2018). Potassium regulates Rubisco biosynthesis and activity, influences the opening and closing of stomata, controls osmoregulation, cell turgor, the transport of water and nutrients across plant tissues and organs and improves cell membrane stability and osmotic adjustment ability (Wang et al., 2013; Hasanuzzaman et al., 2018b; Sardans and Peñuelas, 2021). Various studies have shown the positive effect of sufficient plant-available K in soil in times of drought stress (Wang et al., 2013; Sardans and Peñuelas, 2015, 2021; Hasanuzzaman et al., 2018a). Potassium also acts as an osmolyte and supports stomatal conductance in high temperature (Hasanuzzaman et al., 2018b). It therefore is a key driver in mitigating abiotic crop stress induced by climate change. To our knowledge, the mediating effect of K nutrition on water stress resilience has so far only been investigated for water-limited agroecosystems but not yet for temperate areas such as Switzerland.

Crop response to climatic conditions and the mediating effect of K supply can be analyzed by different approaches such as time series analyses from e.g. long-term experiments (Schmidt et al., 2000), manipulative experiments in controlled environments (Lafta and Lorenzen, 1995), projective modelling (Trnka et al., 2004; Holzkaemper, 2020; Chisanga et al., 2022) or combinations thereof. The advantage of long-term experiments is, that data are usually available for a long period of time from the same location. Hence, site characteristics remain largely similar and only change with agricultural management practices or local climate conditions. This facilitates the study of concomitant variation in climate and nutrient supply traced over decades (Loughin, 2006). Long-term fertilization experiments therefore provide the possibility to analyse long-term changes in soil and plants (Merbach and Deubel, 2007) and, in particular, the effect of plant K nutrition on crop water stress resistance.

The target of this study is the analysis of a 30-year time series of annual crop yield and climate data from the long-term field experiment “Demo” in Zurich Affoltern, Switzerland (Hausherr et al., 2007). The Demo trial is the only Swiss long-term fertilization experiment with varying nutrient input levels by organic, mineral or zero fertilization, which provides annual yield data of the six cash crops wheat, barley, maize, potato, sugar beet and grass-clover ley grown in parallel crop rotations. Confounding effects of seasonal weather conditions on plant performance typical for long-term experiments with crops grown in a single rotation (Loughin, 2006) can thus be neglected. The location of the trial in the Swiss lowland is well suited to represent the agricultural area of Switzerland (Köllner, 2017). The study setup therefore facilitates the identification of species that should be preferably cultivated in Switzerland in the future. The different fertilizer scenarios facilitate the analysis of the effect of K on drought stress.

Therefore, our research questions are, how do individual climate variables, amongst others temperature, precipitation and evapotranspiration, affect the yields of different C_3- and C_4-crops, namely winter barley, potato, sugar beet, spring wheat and maize and how does K supply influence crop response to decreased precipitation? We hypothesize, that the yields of wheat, barley, potato and sugar beet are negatively correlated with temperature while maize yield is not or positively correlated with temperature. Spring precipitation is negatively correlated with wheat and barley yields and summer precipitation is positively correlated with potato, sugar beet and maize yields. Further we hypothesize, that with decreasing precipitation, K supply has a positive effect on yields of summer crops.

2. Materials and methods

2.1. Field experiment and crop management

The Demo trial is a long-term fertilization experiment, which was initiated by Agroscope as a demonstration trial (Hausherr et al., 2007). It is located in Zurich Affoltern (47.425666, 8.516497; 443 m asl), 20 m north of the “Katzenbach” stream at the Agroscope-Reckenholz site. Mean annual air temperature at the site is 9.9 °C and mean annual precipitation is 1020 mm (climate norm 1991–2020; MeteoSwiss, 2023). The soil is an endogleyic Cambisol (Hausherr et al., 2007) with a texture of 47 % sand, 33 % silt and 20 % clay. The soil organic carbon concentration in the topsoil (0–20 cm) is 11–17 g kg^{-1} and the soil pH (H_2O) varies between 6.7 and 7.9 among fertilization treatments (Supplementary Figure 1). The ground water table varies throughout the year but remains above 1.2 m depth (height difference to the “Katzenbach” stream).

The trial was established in 1989 on a managed meadow and the soil was uniformly cultivated with arable crops for two years (1987 / 1988) before the start of the experiment. In those two years, the field was no longer fertilized (Hausherr et al., 2007). The trial covers an area of 0.7 ha and has a non-replicated staggered-start design (Loughin, 2006). It is divided into 7 blocks that are crossed by 8 strips, resulting in 56 plots of 40 m^2 (5 ×8 m). The same crop rotation consisting of 7 crops has been cultivated with the following plants in each block but shifted by one year from one block to the next (Fig. 1): Spring wheat (*Triticum aestivum; hereafter referred to as wheat*), sugar beet (*Beta vulgaris* subsp. *Vulgaris, Altissima Group*), maize (*Zea mays*), potato (*Solanum tuberosum)*, winter barley (*Hordeum vulgare; hereafter referred to as barley*) and two consecutive years of grass clover ley (with *Trifolium pratense*, *Trifolium repens*, *Dactylis glomerata*, *Festuca pratensis*, *Lolium perenne*, *Phleum pratense* L.). The crop rotation and growth periods of the individual crops are illustrated in Supplementary figure 2.

The 8 strips of the Demo trial are treated with different organic and mineral fertilizers to showcase the effect of distinct nutrient deficiencies on the performance of the different summer and winter crops: *Slurry* (cattle slurry adjusted to 100 % mineral N), *NPK* (100 % mineral N, P and K), *NPK+lime* (100 % mineral N, P and K and 2 t ha^{-1} yr^{-1} CaO), *Manure* (25 t ha^{-1} yr^{-1} staple manure), *Zero* (0 % fertilization), *NK* (100 % mineral N and K, 0 % P), *NP* (100 % mineral N and P, 0 % K) and *PK* (100 % mineral P and K, 0 % N). Those differences in nutrient inputs have resulted in distinct differences in soil nutrient concentrations between treatments (Supplementary figure 1). Although the initial soil pH was around 7 (Supplementary figure 1), the NPK+lime treatment has regularly received liming to demonstrate the effect of increased soil pH on the availability and crop uptake of micro nutrients such as boron and molybdenum. Fertilization amounts have been calculated based on the Principles of Agricultural Crop Fertilization in Switzerland PRIF (PRIF 2017: Flisch et al., 2017 and previous editions) and average nutrient inputs in the eight treatments are given in Supplementary table 1.

Each crop was cultivated according to conventional soil management, comprising mouldboard ploughing to a maximum depth of 0.2 m and plant protection according to the Swiss certification scheme Proof of Ecological Performance ("best agricultural practice"; Council, 2013). Each year, the main and by-products were sampled before harvest as

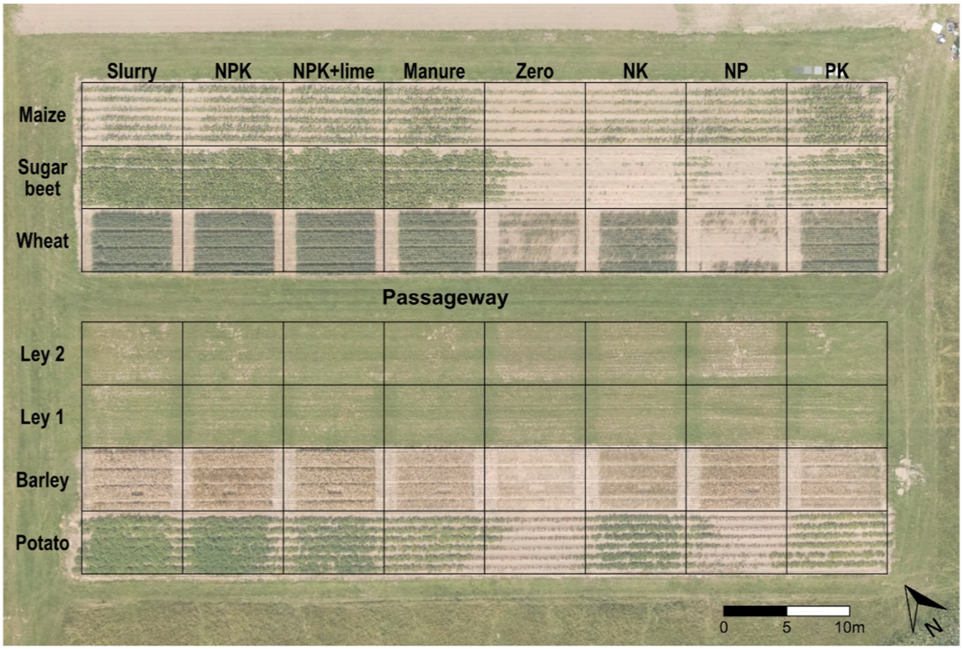

Fig. 1. Design of the Demo trial in 2020. Crops in blocks (rows, top to bottom): maize, sugar beet, wheat, second year of grass clover ley (ley 2), first year of grass cover ley (ley 1), barley and potato. Treatments in strips (columns, left to right): Slurry (cattle slurry adjusted to 100 % mineral N), NPK (100 % mineral N, P and K), NPK+lime (100 % mineral N, P and K and 2 t ha^{-1} yr^{-1} CaO), Manure (25 t ha^{-1} yr^{-1} staple manure), Zero (0 % fertilization), NK (100 % mineral N and K, 0 % P), NP (100 % mineral N and P, 0 % K) and PK (100 % mineral P and K, 0 % N). Each plot is 5 ×8 m.

grab samples (3 ×1 m per plot). In addition, the main products were harvested on the entire plots. Main and by-product yields were determined on dry matter basis and reported in tons per hectare [t ha^{-1}]. All crop residues were removed from the field after harvest. Additionally, the soil was sampled each winter with a combination Edelman auger (4 cm diameter; Eijkelkamp) in 0–20 cm depth in each strip as composite samples from 20 randomly selected spots in each block (averaged over crops). The soil was analyzed for readily plant-available K by extraction of 2 mm sieved fine soil with CO_2-saturated water in a ratio of 1:2.5 and atomic absorption spectrometry (Agroscope, 1996). Soil K was reported as milligram K per kilogram dry soil [mg kg^{-1}]. The extraction with CO_2-saturated water is the official Swiss reference method to determine plant-available K and P and interpretation schemes for fertilization recommendations for both nutrients are well-established (Flisch et al., 2017). The extraction strength of CO_2-saturated water is slightly higher than that of water (Neyroud and Lischer, 2003; Fontana et al., 2022).

As yield formation and fertilization effects are more complex in perennial mixtures than annual crops, the grass clover ley was excluded from the current study. To avoid confounding effects of malnutrition by N or P deficiency, we only used the NPK, NPK+lime and slurry treatments for the analysis of climate effects on crop yields as those treatments showed similar yields over the entire time period for all crops (see 3.2 Crop yields). To determine the influence of K supply on yield response to climate, we also included the NP treatment.

2.2. *Meteo data*

The meteorological data were taken from the station REH in Zurich Affoltern (47.427694 / 8.517953; distance to the Demo trial: 220 m) from the Federal Office of Meteorology and Climatology (MeteoSwiss, 2023). All chosen parameters had a monthly resolution. Since climate mainly influences the yield of the crops during their vegetative phase, seasonal data were calculated in addition to annual means. Based on linear regressions of the individual climate variables and crop yields for each month, two seasons with contrasting relations between climate and yields were defined: spring (March to May) and summer (June to August). Spring and summer are the main seasons for crop growth of the five included annual crops in Switzerland. Summer wheat, maize, potato and sugar beet are sown between March and May, whereas winter barley is sown in autumn and therefore also cultivated during winter. However, its main development starts in March (BBCH 31 – beginning of stem elongation; Harfenmeister et al., 2021), which is why we do not focus on the seasons of autumn and winter in this study. Annual means were calculated for the months January to December. All climate variables used for further analyses are listed in Table 1.

2.3. *Statistical analyses*

To test for changes in climate over the study period 1990–2021, we fitted simple linear models with *Year* as explanatory variable and the climate variable (Table 1, except evapotranspiration) as response and determined the significance of the slope. All climate variables (Table 1) were further subjected to a multivariate Pearson correlation analysis and principal component analysis (PCA) to test for collinearity and non-independence of the variables.

The effects of climate on crop yields were tested in three-step

Table 1
Climate variables, their abbreviations used in this study and their respective units. Spring refers to the time period March-May, summer to June-August and year to January-December. Variables and definitions according to MeteoSwiss.

Climate variable	Abbreviation	Unit
Sum of precipitation spring	Prec_sp	[mm]
Sum of precipitation summer	Prec_su	[mm]
Sum of precipitation year	Prec_yr	[mm]
Mean temperature spring	Temp_sp	[°C]
Mean temperature summer	Temp_su	[°C]
Mean temperature year	Temp_yr	[°C]
Mean evapotranspiration spring	Evapo_sp	[mm]
Mean evapotranspiration summer	Evapo_su	[mm]
Sum of days with heavy rainfall (≥ 30 mm) spring	Heavy_sp	[d]
Sum of days with heavy rainfall (≥ 30 mm) summer	Heavy_su	[d]
Sum of heat days (max. ≥ 30° C) spring	Heat_sp	[d]
Sum of heat days (max. ≥ 30° C) summer	Heat_su	[d]

procedure. First, we did a quality check of the yield and soil K data. In 2013, yield data of barley were missing due to crop failure. Those values were replaced by averaging the yields of barley of the years 2008–2018. We tested for significant changes in climate variables over the past 30 years by means of linear regression. We also estimated the effect of the different treatments on the yield of each of the 5 crops using linear mixed effect models with *Treatment* as fixed effect, *Year* as random effect and *Yield* as response variable. Multiple pairwise comparisons of estimated marginal means (EMMs) of treatments were conducted with Tukey-adjustment of *P*-values resulting in the grouping of EMMs based on statistically significant differences.

Second, we selected 6 common variables that were used as predictor variables for all crops since those variables are easy to reproduce and frequently used in other studies: sum of precipitation in spring, summer and the year and mean temperature in spring, summer and the year. We analysed their influence on yields with multivariate linear mixed effects models (one for each crop) where linear combinations of the 6 variables were modelled as fixed effects, *Treatment* was modelled as random effect and *Yield* was the response variable. We hereafter refer to this analysis as generic analysis. Additionally, we calculated correlation-adjusted t-scores (CAT-scores) by multiplying the square root of the inverse correlation matrix with the vector of t-scores (Zuber and Strimmer, 2009).

Third, we used a stepwise function to analyse the parameters that have the greatest influence on the yield per crop. For this, we used multivariate mixed effects models (one for each crop) where linear combinations of all 12 climate variables (Table 1) were modelled as fixed effects, *Treatment* was modelled as random effect and *Yield* as response variable. Using stepwise analysis with backward-forward selection of predictors and based on the lowest Akaike information criterion, only those variables were kept, which contributed significantly to an improved model fit (Table 2; Venables and Ripley, 2013). We hereafter refer to this analysis as stepwise analysis. Similar to the generic analysis, CAT-scores were calculated.

To analyse the effect of soil K on yield response to precipitation, we first tested general relationships between yield and soil K for all crops in the included treatments (*Slurry*, *NPK*, *NPK+lime*, *NP*). For this, we fitted a linear mixed effects model with *Crop* and *Soil K* as interacting fixed effects, *Year* as random effect and *Yield* as response variable. The same was conducted for the relationships between yield and soil P and Mg, respectively, in order to test for potential concurring nutrient limitations other than soil K in the included treatments. We calculated crop-specific estimated marginal trends for *Soil K, Soil P* and *Soil Mg* in case of significant interactions with *Crop* or, otherwise, determined their general slopes. In addition, the relative importance of *Soil K, Soil P* and *Soil Mg* for *Yield* was determined from simple multivariate linear models by variance decomposition (Lindeman, Merenda, Gold (LMG) scores). We then used a linear mixed effects model with *Soil K* and *Precipitation* as interacting fixed effects, *Treatment* as random effect and *Yield* as response variable. We tested whether the slope for the linear relation between precipitation and yield changed significantly with changing soil K by ANOVA. In case of significance, we derived estimated marginal trends and their associated *P*-values for soil K concentrations between the minimum (2.5 mg kg^{-1} K) and maximum (35.7 g kg^{-1} K) of observed soil K concentration in increments of 0.5 mg kg^{-1} K. Subsequently, we identified the soil K values that resulted in significantly positive slopes between precipitation and crop yield and defined their maximum as threshold soil K that was necessary to mediate yield response to precipitation. The dataset was then split into two groups of low (minimum to threshold soil K) and medium to high (threshold to maximum soil K) to estimate the slopes for those two groups. To verify this procedure, we repeated this analysis for all climate variables and evaluated whether the results were meaningful.

Table 2
Variables kept as fixed effects in linear mixed models after stepwise analysis.

Crop	Fixed effects
Wheat	Heat_sp + Prec_su + Prec_yr + Temp_su + Temp_yr
Barley	Evapo_sp + Heavy_su + Prec_sp + Temp_yr
Maize	Heat_su + Heavy_sp + Heavy_su + Prec_yr + Temp_yr
Potato	Heat_su + Heavy_sp + Heavy_su + Prec_sp + Temp_sp + Temp_su
Sugar beet	Evapo_sp + Heavy_sp

For all mixed models, degrees of freedom were estimated by the Kenward-Roger approach and models were fitted with restricted maximum likelihood (REML). Effects were accepted as significantly different from zero at a significance level of $\alpha < 0.05$.

All calculations, statistical analyses and visualizations were performed in the R environment (R Core Team, 2023) using the packages plyr and dplyr for data management (Wickham, 2011; Wickham et al., 2019), stats and lme4 for fitting simple linear and linear mixed effects models (Bates et al., 2015), psych, emmeans, relaimpo and Rcmdr for statistical analyses (Grömping, 2007; Revelle, 2017; Fox et al., 2022; Lenth, 2023) and ggplot2, ggbiplot and ggpmisc for visualization (Vu et al., 2011; Wickham et al., 2016; Aphalo, 2021).

3. Results

3.1. Climate variables

The annual air temperature varied during the observation period (1990–2021) between 8.3 °C and 11.2 °C (Fig. 2) and resulted in a mean annual air temperature of 9.9 °C. Although the annual temperature showed fluctuations from year to year, temperatures generally increased by 1 °C ($P = 0.001$) over the observation period. Similar to annual temperature, summer (June-August) temperature increased by 1.5 °C over the last 30 years ($P = 0.005$; Fig. 2). Opposite to summer and annual temperatures, spring (March-May) temperature did not change significantly over time. The number of heat days (daily maximum 30 °C or higher) per year varied between 1 and 31 and increased by 3 days per 10 years over the past 30 years ($P < 0.001$; Fig. 2). This was mainly connected to the number of heat days in summer ($P < 0.001$; Fig. 2).

Mean annual precipitation averaged 1015 mm and varied between 750 mm and 1422 mm over the observation period (Fig. 2). Precipitation averaged 249 mm (minimum: 129 mm, maximum: 488 mm) in spring and 339 mm (minimum: 213 mm, maximum: 496 mm) in summer. The number of days with heavy rainfall ($\geq$ 30 mm) also varied among years. In summer, the days of heavy rainfall significantly increased by 1.5 days over the observation period ($P < 0.001$; Fig. 2).

The selected climate variables partly showed high correlations among another, in particular those referring to the summer months. For instance, temperature, evaporation and the number of heat days were strongly positively correlated, whereas precipitation was strongly negatively correlated to both evaporation and the number of heat days (Fig. 3; Supplementary figure 3). The annual and seasonal climate variables only showed significant correlations for temperature and precipitation in spring and the number of heat days in summer (Fig. 3; Supplementary figure 3). Similar to the time series analysis (Fig. 2), the outcome of the PCA indicated a shift of the component scores towards the loading vectors for the climate variables temperature and number of heat days with passing decades (Supplementary figure 3).

3.2. Crop yields

Dry matter yields of the main products of the reference fertilization treatment *NPK* averaged 3.9 t ha^{-1} for wheat, 5.6 t ha^{-1} for barley, 10.9 t ha^{-1} for maize, 9.2 t ha^{-1} for potato and 19.9 t ha^{-1} for sugar beet (Table 3). Long-term fertilization affected yields across all crops and led to significant yield reductions in all treatments except for *Slurry* (all crops) and *NPK+lime* (wheat, barley, maize) when compared to the reference treatment *NPK* (Fig. 3). Wheat had the lowest yield in the treatments *NP* and *Zero*, second lowest yield in *NK*, intermediate yield in *Manure* and second highest yield in *PK*. For barley, yield was lowest in

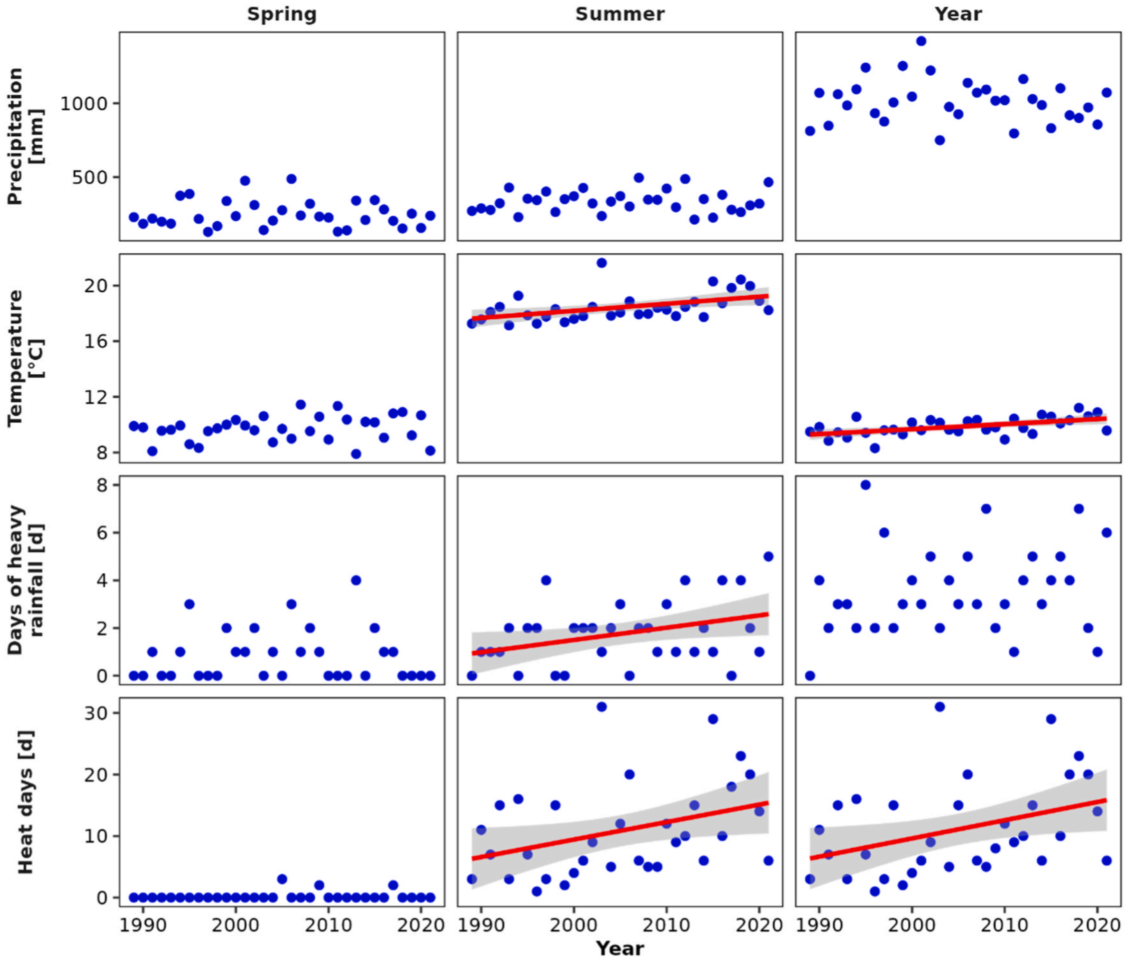

Fig. 2. Climate variables in spring (March-May), summer (June-August) and the entire year (January-December) for the time period 1989–2021 in Zurich Affoltern. Days of heavy rainfall refer to days with rainfall of 30 mm or more. Heat days refer to days with maximum temperature of 30 °C or higher. Trendlines in red and confidence intervals in grey are shown for all linear slopes significantly different from zero (P < 0.05). Data source: MeteoSwiss, 2022.

the treatments *PK* and *Zero* and intermediate in *Manure*, *NK*, and *NP*. Maize yield was more differentiated and lowest in the treatment *NP*, followed by *Zero*, *PK*, *Manure* and *NK*. Potato had the lowest yield in the treatments *NP* and *Zero*, second lowest yield in *Manure* and *PK* and second highest yield in *NK* and *NPK+lime*. Sugar beet yield was lowest in the treatments *Zero* and *NK*, second lowest in *NP* and second highest in *Manure*, *PK* and *NPK+lime* (Fig. 3).

3.3. *Yield response to climate*

The generic models including the six climate variables annual, spring and summer precipitation as well as annual, spring and summer temperature explained 9, 44, 44, 28 and 29 % of the variation in the data for barley, maize, potato, sugar beet and wheat, respectively (Fig. 4). In general, summer temperature was negatively correlated to crop yields, although this effect was significant for maize, potato and wheat only (Fig. 4). The remaining variables were contrarily correlated to the yields of the different crops. The stepwise models including only those climate variables with the greatest influence on the yield per crop explained 32, 53, 51, 28 and 35 % of the variation in the data for barley, maize, potato, sugar beet and wheat, respectively (Fig. 5). The stepwise analysis thereby provided a considerably better model fit for barley and slightly better model fits for maize, potato and wheat compared to the analysis with the generic models.

Wheat yield was negatively related to annual precipitation ($P = 0.002$) and summer temperature ($P < 0.001$) according to the generic analysis (Fig. 4). The same negative relation to annual precipitation ($P < 0.001$) and summer temperature ($P < 0.001$) was revealed by the stepwise analysis. In addition, a negative relation was found to the number of heat days ($P = 0.005$; Fig. 5).

Barley yield was positively related to summer precipitation ($P = 0.021$; generic analysis; Fig. 4) and evapotranspiration in spring ($P < 0.001$), precipitation in spring ($P < 0.001$) and days of heavy rainfall in summer ($P < 0.001$; stepwise analysis; Fig. 5). Evapotranspiration in spring was by far the most important variable for barley yield (highest CAT score; Fig. 5).

According to both the generic and stepwise analyses, maize yield was positively related to mean annual temperature (both $P < 0.001$), which was the most important variable with the highest CAT score, and negatively to annual precipitation ($P = 0.016$ and $P < 0.001$, respectively; Fig. 4; Fig. 5). In addition, maize yield was negatively related to summer temperature ($P < 0.001$; generic analysis; Fig. 4) as well as the number of heat days ($P < 0.001$) and days of heavy rainfall ($P = 0.006$; stepwise analysis; Fig. 5).

Potato yield was most strongly and negatively related to summer temperature, as shown by the highest CAT scores in both the generic and stepwise analyses (both $P < 0.001$; Fig. 4; Fig. 5). Potato yield was also negatively related to spring precipitation ($P = 0.002$) but positively to spring temperature ($P < 0.001$), days of heavy rainfall in spring ($P = 0.012$) and summer ($P = 0.015$) and number of heat days in summer ($P = 0.024$) according to the stepwise analysis (Fig. 5).

Sugar beet yield was negatively related to spring precipitation ($P =$

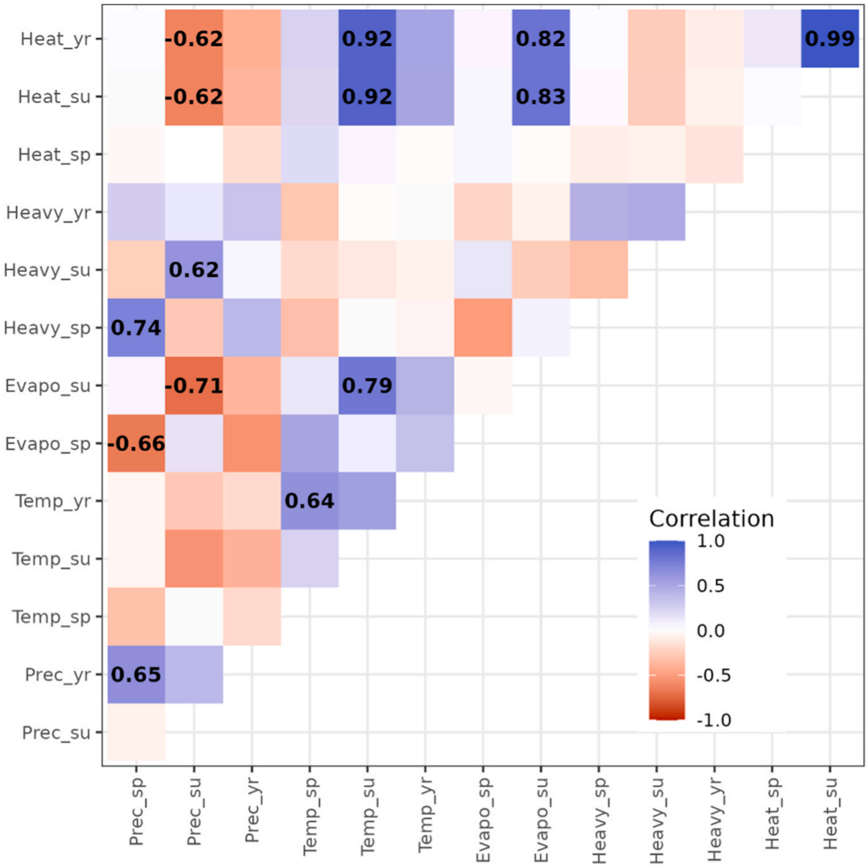

Fig. 3. Multivariate Pearson correlation coefficients for the climate variables. Significant correlation coefficients are shown in bold font. Please refer to Table 1 for the abbreviations of the climate variables.

Table 3
Dry matter yields (means ± standard deviations) of main products (wheat, barley, maize: grain; potato: tuber; sugar beet: beet) for each crop planted in the reference fertilization treatment NPK averaged for the time period 1990—2021. Years of extreme values are provided in brackets.

Crop	Mean [t ha^{-1}]	Minimum [t ha^{-1}]	Maximum [t ha^{-1}]
Wheat	3.9 ± 0.9	2.0 (1998)	5.7 (2011)
Barley	5.6 ± 1.0	3.5 (1993)	8.0 (1995)
Maize	10.9 ± 2.3	6.2 (2012)	15.7 (2011)
Potato	9.2 ± 2.1	4.9 (2017)	13.9 (2011)
Sugar beet	19.9 ± 4.3	10.0 (2006)	30.2 (2011)

0.008; generic analysis; Fig. 4) and days of heavy rainfall in spring ($P = 0.031$) and positively to evapotranspiration in spring ($P = 0.002$; stepwise analysis; Fig. 5).

3.4. Yield response to precipitation under varying soil potassium

The general relationships between yield and soil K in the included treatments (*Slurry, NPK*, *NPK+lime*, *NP*) were significantly positive for all crops (Supplementary figure 4). By contrast, soil P and soil Mg were not significantly related to yield of any crop in those treatments except for the positive relationship of sugar beet yield to soil Mg (Supplementary figure 4). However, the relative importance of soil K for sugar beet yield was still 25-times higher than that of soil Mg (Supplementary figure 5).

Maize was the only crop with a significant interaction effect of precipitation and extractable soil K concentration on yield, which applied only to spring precipitation ($P = 0.043$). For the other crops and precipitation variables, the slopes for the relations between precipitation and yield did not differ with changing soil K (Supplementary table 2). For maize, the slope of the relation between spring precipitation and yield was significantly positive for low soil K values up to 7.0 mg kg^{-1} ($P = 0.012$) and did not differ from zero for higher soil K up to the maximum value of 35.7 mg kg^{-1} ($P > 0.05$). Hence, we identified the threshold soil K value that is necessary to mediate maize yield reductions at reduced spring precipitation as 7.0 mg kg^{-1}. Accordingly, the data was separated into two groups of low ($\leq$ 7.0 mg kg^{-1}) and medium to high ($>$ 7.0 mg kg^{-1}) soil K concentration (Fig. 6). The slope of the relation between spring precipitation and yield in the low soil K group was 0.011 ($P = 0.012$), indicating that maize yield was reduced by approximately 1 t ha^{-1} per 100 mm reduction of spring precipitation (Fig. 6). By contrast, the slope in the medium to high soil K group was not different from zero, indicating that maize yield was not affected by spring precipitation (Fig. 6).

Complementary analyses of the effect of soil K on yield response to the other climate variables revealed no significant interaction effect for any crop other than maize (Supplementary table 2). Maize yield showed a significant positive relationship to annual temperature only when soil K was above 7.5 mg kg^{-1} (Supplementary figure 6), supporting the result of maize yield response to annual temperature for the treatments *Slurry, NPK, NPK+lime* (Fig. 5). Similarly, maize yield was significantly positively related to evapotranspiration in spring when soil K was above 16.5 mg kg^{-1} (Supplementary figure 7), supporting the result of the positive effect of soil K on yield response to precipitation (Fig. 7). Hence, those results will not be discussed in more detail.

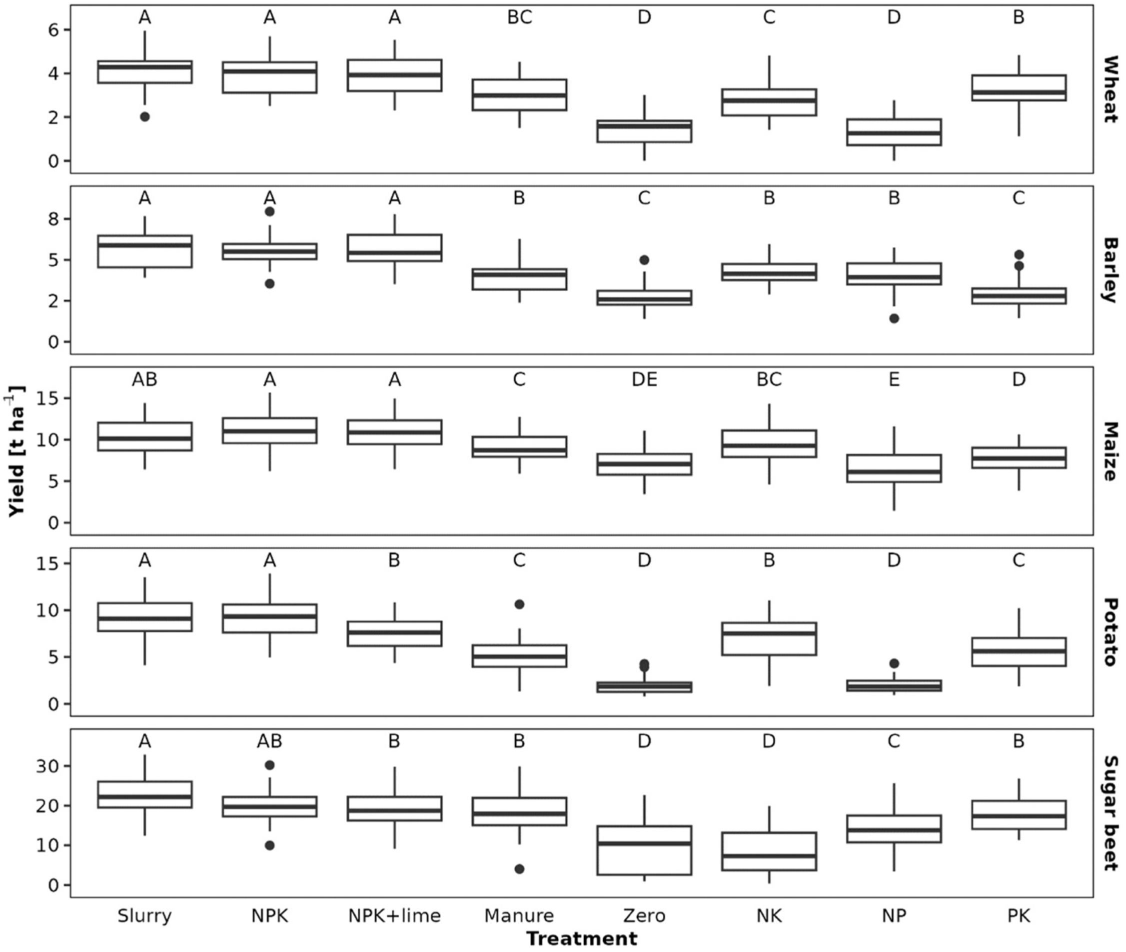

Fig. 4. Crop yields of wheat, barley, maize, potato and sugar beet per treatment for the time period 1990–2021 in Zurich Affoltern (n = 30 for barley, n = 31 for all other crops). The eight treatments were fertilised with different organic and mineral fertilizers: Slurry (cattle slurry adjusted to 100 % mineral N), NPK (100 % mineral N, P and K), NPK+lime (100 % mineral N, P and K and 2 t ha^{-1} yr^{-1} CaO), Manure (25 t ha^{-1} yr^{-1} staple manure), Zero (0 % fertilization), NK (100 % mineral N and K, 0 % P), NP (100 % mineral N and P, 0 % K) and PK (100 % mineral P and K, 0 % N). Capital letters describe statistically significant different classes (treatments not sharing a letter within a crop have significantly different yields).

4. Discussion

4.1. Climate

During the time period the Demo trial has been maintained, both annual and summer temperatures have significantly increased according to the 30-year time series recorded at the meteorological station in Zurich Affoltern. There has been also an increase in extreme events in summer, namely the number of heat days and days of heavy rainfall. This is supported by the outcome of the PCA that shows a shift towards higher temperature, evaporation and number of heat days irrespective of season in the three decades. The same pattern applies to most of the meteorological stations across Switzerland (Scherrer et al., 2016). In contrast to temperature, precipitation showed no change throughout the last three decades, which is in line with data from other meteorological stations across Switzerland and climate model outputs (Zubler et al., 2014). Similar trends were observed in Germany and Central Europe (Kaspar et al., 2017).

The high correlation of some of the included climate variables, in particular temperature, precipitation, evaporation and number of heat days in summer, is in line with numerous regional findings (Solomon et al., 2007). Dry conditions in summer entail less evaporative cooling which leads to higher temperature, whereas summers with high amounts of rainfall are generally cooler. The positive correlations between annual and spring temperature as well as annual and spring precipitation might be rather region-specific as more complex relationships of atmospheric circulation patterns in Europe and individual seasons have been shown to vary between regions and time periods (Zveryaev and Gulev, 2009; Hirschi and Seneviratne, 2010).For Switzerland, three climate-change scenarios were created for the CH2018 climate report (Croci-Maspoli et al., 2018): No climate protection (RCP8.5), medium climate protection (RCP4.5) and strong climate protection (RCP2.6). According to the CH2018 RCP4.5 scenario, summer precipitation is expected to decrease by 7 %, although with a high amount of uncertainty (-25 % to +7 %). Spring precipitation is projected to increase by about 6 % (-1 % to +19 %). Therefore, trends for changes in precipitation are expected to be rather weak (Croci-Maspoli et al., 2018), which could be also observed in Zurich Affoltern. By contrast, the CH2018 RCP4.5 scenario shows a clear trend for temperature and extreme events: Spring temperature is predicted to increase by 0.9 °C to 2.3 °C, summer temperature by 1.6 °C to 3.6 °C and the number of heat days by 4 days until the end of the century (Croci-Maspoli et al., 2018). However, there have already been substantial increases in both summer temperature (1.5 °C) and the number of heat days (3 days per 10 years) over the past 30 years in Zurich Affoltern. Hence, this trend developed faster in the past years than projected in the RCP4.5 scenario, indicating that RCP8.5 projections might be more realistic for Switzerland.

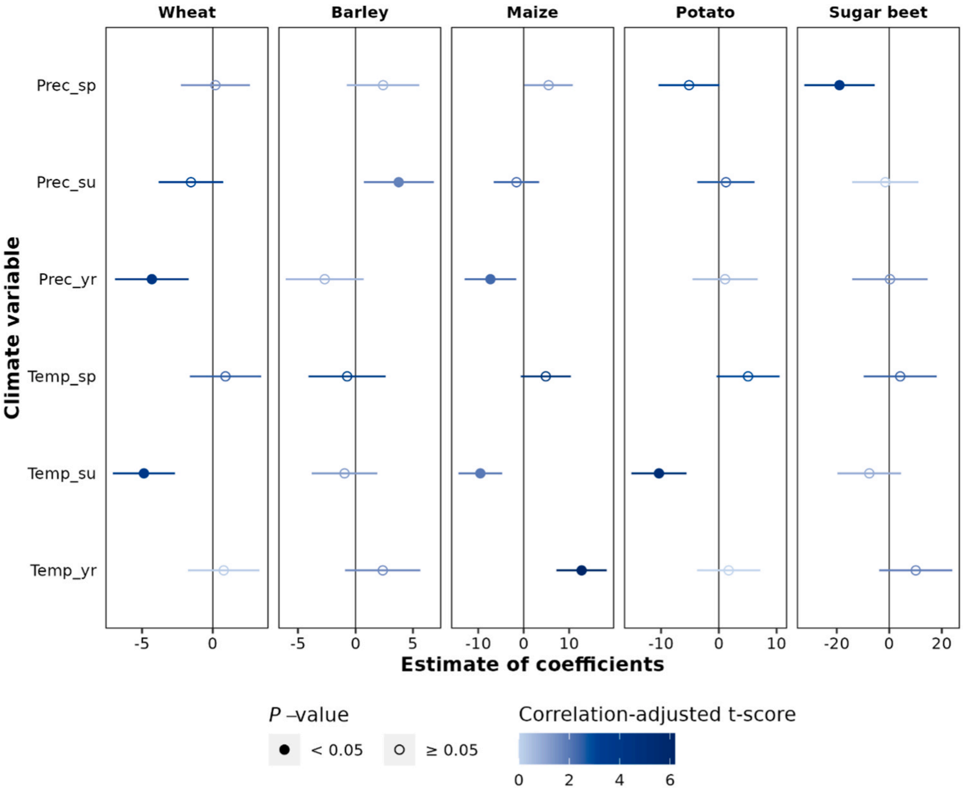

Fig. 5. Coefficients (estimates and 95 % confidence intervals) of the climate variables explaining crop yields in generic models including the same explanatory variables for wheat (R^2= 0.29), barley (R^2= 0.09), maize (R^2= 0.44), potato (R^2= 0.44) and sugar beet (R^2= 0.28). Significance and relative importance of coefficients are represented by P-values and CAT-scores (correlation-adjusted t-scores), respectively. Prec_sp, Prec_su and Prec_yr, sum of precipitation in spring, summer and the year, respectively; Temp_sp, Temp_su and Temp_yr, mean temperature in spring, summer and the year, respectively.

4.2. Crop yields

Spring wheat yield in the *NPK* treatment of the Demo trial (3.9 t ha^{-1}) is on average lower than spring wheat yields in Switzerland (5.5 t ha^{-1}; Brabant et al., 2006) and wheat yields in France (6.1 t ha^{-1}; van der Velde et al., 2012). Yield differences between Switzerland and other European countries were also shown in another study (Schils et al., 2018) and likely arise from differences in breeding targets (Stamp et al., 2014). The reason for the exceptionally low spring wheat yield in the Demo trial is, however, unclear. In addition to *Zero*, *NP* is the treatment with the lowest yield, suggesting that K is the most limiting nutrient in the Demo trial for spring wheat. Potassium is the key driver of processes governing plant-water-relations (Sardans and Peñuelas, 2021), which is especially important for summer crops that are metabolically most active when temperatures and evapotranspiration are high.

Barley yield in the Demo trial averages 5.6 t ha^{-1} and corresponds to yields observed in other agricultural trials across Central Europe (4.9–7.0 t ha^{-1}; Körschens, 1994; Rötter et al., 2012; Panek and Gozdowski, 2021). Barley has the lowest yield in the treatment *PK* apart from *Zero*. As it is grown very early in the year, low temperature hampers mineralization of the soil organic matter and therefore restricts inherent soil N resupply (Miller and Geisseler, 2018), which might explain why N is the most limiting nutrient for barley in this study.

Maize yields in the Demo trial (10.4 t ha^{-1}) are also similar to yields observed in Germany and France (8.8–20.8 t ha^{-1}; Schmidt et al., 2000; van der Velde et al., 2012; Huynh et al., 2019). Similar to wheat, maize is a summer crop and similarly affected by K deficiency in the *Zero* and *NP* treatments.

The average dry matter yield of potato in the Demo trial (9.1 t ha^{-1}) is higher than the dry matter yield in the long-term fertilization experiment in Halle, Germany (6.2 t ha^{-1}; Schmidt et al., 2000). The potato yield in the Demo trial corresponds to 43 t ha^{-1} fresh weight and is similar to the average potato yield of 42 t ha^{-1} fresh weight in the top five potato producing countries in Europe (France, Germany, Netherlands, UK and Belgium; Goffart et al., 2022). Like wheat and maize, potato is planted in summer and is therefore most susceptible to K deficiency in the *Zero* and *NP* treatments.

Sugar beet dry matter yield is 19.9 t ha^{-1} in the Demo trial, corresponding to 94 t ha^{-1} fresh weight, which is similar to yields of 80–95 t ha^{-1} in France (Řezbová et al., 2013) but higher than average yields of 66 t ha^{-1} in the European Union (Haß, 2022). Apart from the treatment *Zero*, *NK* results in the lowest sugar beet yield. Phosphorus is highly immobile in the soil and plant P uptake is largely driven by root interception of soil P reservoirs (Hawkesford et al., 2012). The poorly developed root system of the sugar beet plant makes this crop more prone to P deficiency than other crops (Bhadoria et al., 2002). In summary, crop yields in the Swiss Demo trial are mostly within observed ranges of other Central European trials which suggests that the observations in the Swiss Demo trial are largely representative for Central Europe.

The treatments *Slurry* and *NPK* produce similar yields for all crops in the Demo trial. Similar effects of slurry application can be seen in other fertilization experiments (Hernández et al., 2013; Hlisnikovský et al., 2022) and reflect optimal nutrient supply. The amount of applied mineral N (Supplementary table 2) is aligned with applied N in *NPK* according to Swiss agricultural practice (Richner et al., 2017). However, applied total N (Supplementary table 2) by far exceeds crop demand (Sinaj et al., 2017) and it is likely that considerable amounts of unused N are lost to the environment by leaching and gaseous emissions (Richner et al., 2017). The *Manure* treatment yields consistently lower yields for all crops compared to *NPK* and *Slurry*, because of the low amount of applied mineralized N (Supplementary table 2) and, consequently, severe N limitation for the crops (Richner et al., 2017).

For wheat, barley and maize, the treatment *NPK+lime* also produces

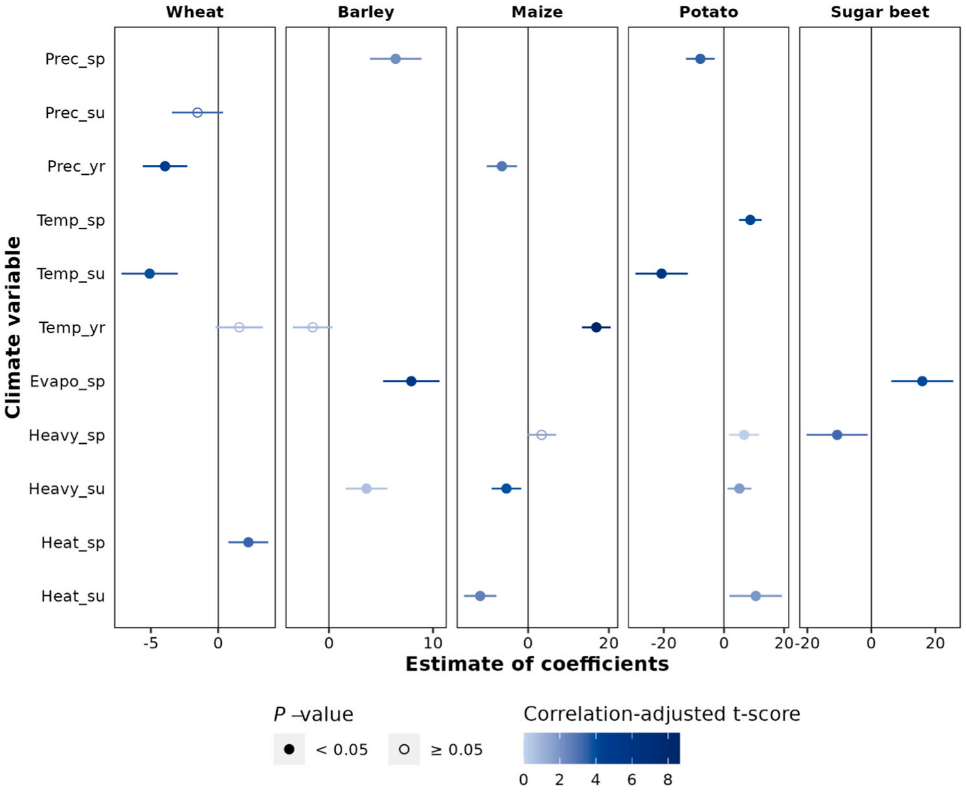

Fig. 6. Coefficients (estimates and 95 % confidence intervals) of the climate variables explaining crop yields in stepwise models including only the most important explanatory variables for wheat ($R^2 = 0.35$), barley ($R^2 = 0.32$), maize ($R^2 = 0.53$), potato ($R^2 = 0.51$) and sugar beet ($R^2 = 0.28$). Significance and relative importance of coefficients are represented by P-values and CAT-scores (correlation-adjusted t-scores), respectively. Prec_sp, Prec_su and Prec_yr, sum of precipitation in spring, summer and the year, respectively; Temp_sp, Temp_su and Temp_yr, mean temperature in spring, summer and the year, respectively; Evapo_sp and Evapo_su, mean evapotranspiration in spring and summer, respectively; Heat_sp and Heat_su, sum of heat days in spring and summer, respectively; Heavy_sp and Heavy_su, sum of days with heavy rainfall in spring and summer, respectively.

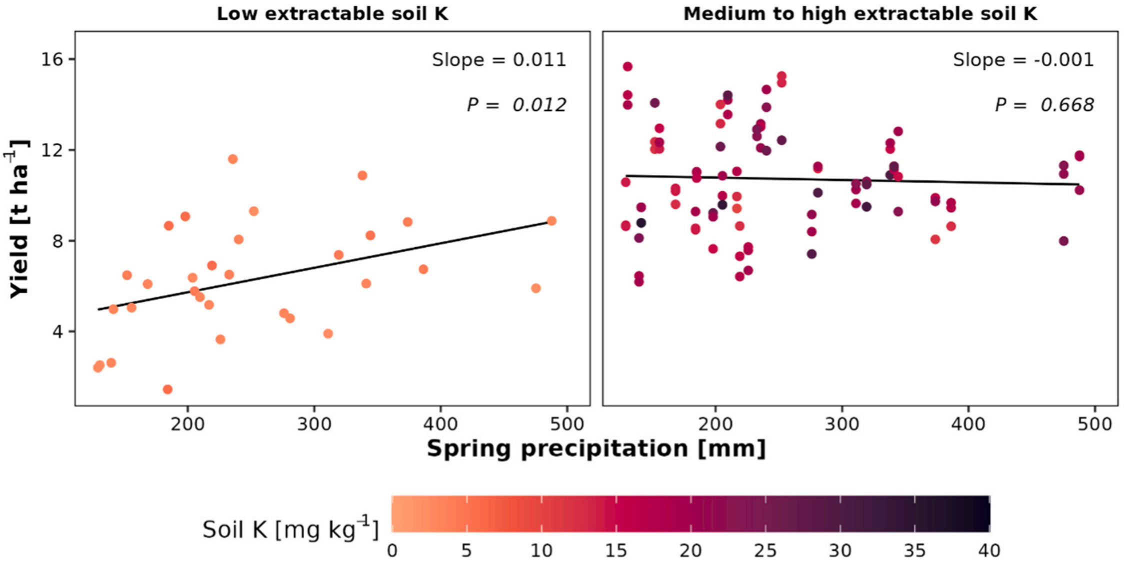

Fig. 7. Yield of maize in relation to precipitation in spring (March-May) as affected by low (2.5–7.0 mg kg^{-1}) and medium to high (7.1–35.7 mg kg^{-1}) soil potassium (K) concentration for the time period 1990–2021 in the Demo trial. Soil K concentration was measured in CO_2-saturated water in a ratio of 1:2.5 by atomic absorption spectrometry (Agroscope, 1996).

similar yields as *NPK*. After 30 years of liming, the difference in pH between *NPK* and *NPK+lime* has leveled out at 0.5 pH units (Supplementary figure 1). As the initial pH of the soil was around 7, liming would have neither been necessary nor recommended for this site (Flisch et al., 2017) but was established to intentionally induce micronutrient deficiency in sensitive crops. The yields of potato and sugar beet are significantly lower in *NPK+lime* than *NPK*, presumably due to reduced boron availability (Barrow and Hartemink, 2023), which affects dicotyledonous plants such as potato and sugar beet more severely than monocotyledonous plants such as cereals and maize (Broadley et al., 2012).

4.3. Impact of climate variables on crop yields

The two different methods to estimate the impact of climate on crop yields – a generic model with the same temperature and precipitation variables for all crops and a stepwise model with only relevant climate variables for each crop – show partly different results. The significance of coefficients can be biased when variables are strongly collinear and/or when important predictor variables are missing, which is often indicated by an overall poor model fit (Krzywinski and Altman, 2015). This becomes clear in the case of maize and potato, which show similar results for the most important predictor variables irrespective of the model. For both crops, the model fit is comparatively good ($R^2 = 0.44–0.53$). By contrast, the results for barley and sugar beet differ strongly between models, which also fit the data rather poorly ($R^2 = 0.09–0.32$). Hence, in the following, we focus on the most prominent and conclusive results.

Wheat yields are negatively correlated with annual precipitation but not seasonal precipitation in the Demo trial. Potentially, higher precipitation, especially during winter, delays sowing of this summer crop and thus shortens the growing season and/or increases the pressure of pests and diseases during vegetative growth (Büchi et al., 2019). However, since precipitation shows no trend in the Demo trial, it is difficult to estimate its effect on wheat yield in the future. By contrast, summer temperatures have increased during the last 30 years and are expected to further increase in the future (Croci-Maspoli et al., 2018). A negative impact of increasing temperature on wheat yields has not only been observed in our study but also previously in France (Brisson et al., 2010). High temperature induces early senescence and incomplete grain filling in small grain cereals (Peltonen-Sainio et al., 2010) and is therefore projected to become the most severe climatic limitation for wheat cultivation in Switzerland in the future (Holzkämper et al., 2015).

Barley shows high yields in years, when evapotranspiration is high in spring. Evapotranspiration is closely linked to temperature, which has not revealed a clear trend for the past 30 years. Consequently, there is also no increase or decrease in barley yields. In general, the low coefficients of determination for both the generic and stepwise analyses show that meteorological conditions during spring, summer and the year do not have a large effect on barley. As barley is the only crop in our study that is sown in the preceding autumn, climate anomalies during winter might have an influence on crop performance (Wójcik-Jagła and Rapacz, 2023) but were not included in our analyses. In general, this crop easily adapts to different environmental conditions and can therefore be cultivated under varying climatic scenarios without major yield decreases (Newton et al., 2011). In dry areas like North Africa, barley is a staple food and frequently produced (Grando and Macpherson, 2005). Based on a study covering longer time periods, barley yields are not predicted to change until the end of the century in Serbia despite climate change (Daničić et al., 2019). As climate model predictions for Switzerland do not predict any major changes in spring precipitation or temperature (Croci-Maspoli et al., 2018), we assume that barley is very likely to deliver reliable yields in the Demo trial also in the future if optimal nutrient supply is ensured.

Maize yields have been positively influenced by rising annual and spring temperatures in the Demo trial, as the growing season has been extended and temperatures have come closer to the temperature optimum of 30–35 °C of the plant (Bonhomme, 2000; Sánchez et al., 2014). However, the negative correlation between the number of heat days in summer and yield suggests that the temperature optimum of maize is surpassed in summer. In other European countries such as Germany, France and Belgium, maize was also found to be susceptible to heat stress (Hawkins et al., 2013; Ceglar et al., 2018). Among the major photosynthetic processes in C4 metabolism, namely Rubisco activation, activities of PEP carboxylase and pyruvate phosphate dikinase, and photosystem II stability, the gradual inactivation of Rubisco was found to be the most heat-sensitive step inhibiting yield at leaf temperature above 30 °C (Crafts-Brandner and Salvucci, 2002). In addition, we find negative effects of annual precipitation and days of heavy rainfall events in summer on maize yield in the Demo trial. Those effects might rather be linked to secondary effects of rainfall on maize yields such as late sowing or hailstorm damage (Battaglia et al., 2019) than to flooding or water logging. In Switzerland, water scarcity between flowering and grain filling was found to be one of the main climatic limitations for maize cultivation (Holzkämper et al., 2015). Consequently, irrigation demands are expected to increase in order to uphold maize production beyond 2050 (Holzkaemper, 2020; Hristov et al., 2020). However, due to the shallow ground water table at the site and the close vicinity to the "Katzenbach" stream, water scarcity might be generally a minor issue in the Demo trial.

Potato yields are most strongly driven by climatic conditions, as underlined by the highest coefficients of determination of the model fits. Similar to maize, potato shows a negative correlation of yield and temperature in summer. Above 35°C, C_3 plants close their stomata and reduce photosynthesis (Bonhomme, 2000). Likewise affected by heat stress is tuber development, and hence, the amount and size of the harvested potatoes (Reynolds and Ewing, 1989). In particular, high temperature increases secondary tuberization, which in turn has a negative effect on tuber size and, consequently, yield (Rykaczewska, 2015). Since summer temperatures will continue to rise, potato cultivation might become increasingly difficult in the Demo trial. For Europe, simulations of the effect of climate change on potato yields showed both decreasing (-15 % to −19 %; Hijmans, 2003) and increasing (+5 to +25 %; Raymundo et al., 2018) trends but those projections were characterized by a high amount of uncertainty depending on the data source and model.

Sugar beet yield is negatively influenced by ample precipitation and heavy rainfall events in spring in the Demo trial. Delayed sowing due to wet conditions in spring can have a negative effect on sugar beet yields (Petkeviciene, 2009). However, in other trials, major climatic limitations for sugar beet were related to drought stress (Jones et al., 2003; Kenter et al., 2006; Richter et al., 2006). This is not visible in the Demo trial, which might be a direct effect of the close vicinity to ground and surface water, and therefore, generally sufficient water supply also in periods of low precipitation. As for barley, the overall fit of both models to the data is rather poor and yield response might be driven by other factors than those included in the models (Krzywinski and Altman, 2015).

In Swiss agricultural practice, around 22 % of arable land is dedicated to wheat production, 11 % to barley, 15 % to grain and silage maize, 3 % to potato and 4 % to sugar beet production (FOAG, 2022). Hence, besides grass-clover ley, which occupies around 29 % of arable land in Switzerland, cereals and maize are the most important crops in the Demo trial in terms of representativeness for agricultural practice. In order to avoid the negative impact of heat stress on wheat, maize and potato yields in the future, different strategies can be pursued, such as changing to earlier varieties or sowing and harvest dates (Rogger et al., 2021; Zhao et al., 2022; von Gehren et al., 2023), breeding and selecting for more heat-tolerant varieties (Akter and Rafiqul Islam, 2017) or switching crops in rotations (Rising and Devineni, 2020). In a recent modelling and review study, durum wheat, quinoa and lentil, amongst others, were identified as climate-adapted alternative crops for Swiss rainfed conditions (Heinz et al., 2024). In addition, rice and sorghum have been in the focus of research and variety testing programs in Switzerland since some years (Hiltbrunner et al., 2012; Gramlich et al., 2021). Those crops might be viable alternatives for Swiss agricultural practice under continued temperature increases.

4.4. Positive effect of potassium supply on maize yields under low spring precipitation

There is no positive relation between precipitation and maize yields in the treatments with sufficient nutrient supply, i.e., *NPK*, *NPK+lime* and *Slurry*, presumably due to the favorable site conditions regarding water availability. Only for the treatment with distinct K deficiency (*NP*), a positive relation between yield and precipitation can be observed. The significant interaction between spring precipitation and K availability in the soil for maize yields in the Demo trial implies that K fertilization plays an important role for the drought resilience of maize. This was also shown by other studies around the world (Pettigrew, 2008; Aslam et al., 2012; Ul-Allah et al., 2020). Under non-stressed conditions, maize has a higher water use efficiency than C_3-plants, as the CO_2-concentrating mechanism of the C_4-metabolism facilitates greater CO_2 diffusion at lower leaf conductance and, therefore, reduced water loss by transpiration during photosynthesis. However, under drought stress, stomatal activity and photosynthetic CO_2 uptake are more severely limited in C_4- than C_3-plants, because the C_4-metabolism operates close to the inflection point of the photosynthetic CO_2 response (Wand et al., 2001; Guidi et al., 2019). Potassium regulates the water transport in plants and positively affects the stomatal activity. This is reflected by the positive influence of K supply in times of less precipitation for maize but not for the C_3-crops in this study. In addition, K nutrition directly affects root growth and root elongation (Zhao et al., 2016; Sustr et al., 2019), which are most active in the vegetative phase until flowering (Gregory, 2007), i.e. during spring and early summer. With a well-developed root system, maize plants can access water and nutrients more easily (Sustr et al., 2019), which might explain the positive relation between maize yields and precipitation under low soil K in spring but not summer.

The threshold of 7 mg K kg^{-1} soil, beyond which K availability does not affect yield response to spring precipitation in the Demo trial, is very low compared to the average K availability of 34 mg K kg^{-1} soil in Swiss agricultural soils (Agroscope and FOAG, unpublished data). Only 5 % (13’000) of the approx. 248’000 agricultural fields that have been analyzed for soil K availability in the past 10 years within the frame of the Swiss subsidy scheme Proof of Ecological Performance (FOAG, 2020) fall below that threshold. On the one hand, the main agricultural area in the Swiss lowland is situated on K-rich Cambisols (Veit and Gnägi, 2014). On the other hand, for soil K values of 12–30 mg kg^{-1} (and a clay content of 20–30 %), regular K fertilization is recommended to replace crop K offtake according to the Principles of Fertilization of Agricultural Crops in Switzerland (Flisch et al., 2017). Yet, as the threshold of 7 mg K kg^{-1} soil derived from crop response at just one site with favorable water availability can be considered as rather conservative, the threshold might be much higher in individual situations and likely varies with soil and landscape properties.

During the time period the Demo trial has been maintained, the percentage of Swiss farms that needed to purchase water for irrigation has increased from 63 % to 77 % and spending for irrigation water has more than doubled from 500 to 1200 CHF $year^{-1}$ per farm (inflation-adjusted; Seiler et al., 2022). A major part of this change is attributed to increasing natural water shortage and evapotranspiration due to climate change (Akademien der Wissenschaften Schweiz, 2016). For maize, irrigation demands are projected to increase by up to 40 % to 120–320 mm $year^{-1}$ until the end of the century in order to maintain current yield levels (Holzkaemper, 2020). Hence, total irrigation costs (including infrastructure) may become as high as 1’200–2’500 CHF ha^{-1} to avoid yield reductions of up to 5–6 t ha^{-1}, as demonstrated for grain maize in the canton of Basel-Country (Zorn and Lips, 2016). Based on the findings in our study, balanced K supply can mediate yield reductions of 1 t ha^{-1} per 100 mm decrease in precipitation and, thus, alleviate irrigation water demands and costs. Against this background, the soil K fertility classes and K fertilization guidelines (Flisch et al., 2017) might need to be revisited.

4.5. *Suitability of the experimental design*

The Demo trial has a staggered start design (Loughin, 2006), which allows to analyse the impact of environmental conditions on crop performance for several crops in parallel in a crop rotation experiment. It is the only long-term experiment in Switzerland with different organic and mineral fertilization treatments and distinct nutrient deficiencies of N, P and K in several crops simultaneously. Compared to a classical design with individual crops grown in rotation, the staggered start design allows the statistical analysis of temporal and environmental effects separately and in interaction (Loughin, 2006; Tejera et al., 2019). Confounding effects of annual weather impacts on crop yields occurring only once every couple of years have been shown to be a major drawback for the analysis of yield response to treatment factors (Loughin, 2006). In our study, those effects can be neglected because of the staggered start design.

However, due to distinct nutrient deficiencies in the individual treatments, interaction effects of different nutrients on yield and crop response to climatic conditions cannot be addressed with the design of the Demo trial. For this, crossed combinations of different levels of fertilization among the treatments would be needed. Nevertheless, the individual effects of nitrogen and phosphorus supply on crop response to climatic conditions can be investigated in future studies and qualitatively compared to our findings on the positive effect of K supply on maize yields.

Natural water availability at the site can be considered as rather high due to the close vicinity to ground and surface water (20 m to the “Katzenbach” stream). Consequently, the site is not particularly prone to drought stress and the observed effects are rather conservative for the average of Switzerland. Hence, the applicability of our findings to other sites needs to be thoroughly verified based on pedoclimatic site conditions. Due to the proximity of the meteorological station (220 m), the influence of climate on crop yields can be estimated very accurately. We have chosen a monthly resolution to provide a seasonal analysis of spring and summer, although it does not allow for an estimate of how uniformly the rain fell within a month (Knapp et al., 2008) or how seasonal climate conditions during individual crop growth stages influenced crop yields (Schierhorn et al., 2021). In addition, climate conditions during the preceding winter might have an impact on crop performance, in particular the frequency, degree, and length of extreme winter warming events for winter barley (Wójcik-Jagła and Rapacz, 2023), but were not included in this study. Consequently, the seasonal weather influences on crop yields are not fully covered in our study but should be explored in more detail in future analyses.

The chosen crops are among the most common arable crops in Switzerland (FOAG, 2022) and the crop rotation is in line with federal proposals and common agricultural practices (Jeangros and Courvoisier, 2019). Although the location of the Demo trial in Zurich Affoltern is representative of the agricultural area in the Swiss lowland in terms of altitude, temperature and precipitation, only one location could be considered in this work. In order to increase the explanatory power, several trials of this kind would be needed in Switzerland. Although field replications are missing for the individual crops and treatments per year, the staggered start design and long observation period, resulting in numerous temporal replications, allow for robust data analysis and general conclusions regarding plant-soil-climate relations from this trial. The long-term data of the Demo trial would therefore be suitable to analyse further effects of (un-) balanced crop nutrition on crop resilience to different biotic and abiotic stresses.

5. Conclusions

The joint evaluation of crop yields in the Swiss Demo trial and the climate variables of the meteorological station at Zurich Affoltern revealed a negative impact of rising summer temperature on yields of wheat, maize and potato. This refutes our hypothesis that maize would not or positively be influenced by increasing temperature. Similarly, our findings do not support our initial hypothesis that spring precipitation is negatively correlated with cereal yields and summer precipitation is positively correlated with yields of potato, sugar beet and maize. Apart from barley and sugar beet, whose yields were positively and negatively affected by spring precipitation, respectively, none of the crops showed a response to seasonal precipitation. Our hypothesis, that K supply has a positive effect on yields of summer crops when precipitation decreases, could only be confirmed for maize response to spring precipitation but not for the other summer crops and precipitation variables.

Based on our analyses of yield response to climate conditions and the future climate scenarios for Switzerland, crop rotations with less heat-sensitive species than wheat and potato should be considered in the future. Those crops could partly be replaced with other crops, such as barley or durum wheat, and early-maturing varieties. Further, breeding and variety selection towards more heat-tolerant genotypes will be a key factor in adapting crop rotations to climate change. The importance of balanced K supply becomes evident for mediating yield reductions under increasing natural water shortage and evapotranspiration due to climate change. In order to keep future irrigation demands and costs as low as possible, the soil K fertility classes in the Swiss K fertilization guidelines might need to be revisited, which requires studies on yield response to soil K availability and water supply in multiple environments. Our study is one of a few long-term observations that show the impact of climate variation on crop yields and highlights the potential of K management as a climate change adaptation measure.

CRediT authorship contribution statement

Jonathan Frei: Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Guido L. B. Wiesenberg:** Writing – review & editing, Supervision, Conceptualization. **Juliane Hirte:** Writing – review & editing, Visualization, Validation, Project administration, Data curation, Conceptualization.

Declaration of Competing Interest

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

Data availability

Data will be made available on request.

Acknowledgements

We sincerely thank Ulrich Walter and René Flisch for the initiation of the Demo trial in 1989 and Ernst Brack, Hans-Ulrich Zbinden, Katrin Casada, Karin Meier-Zimmermann and many coworkers, civil servants and interns for the maintenance of the trial. We also thank Fabien Durand-Maniclas for support in data curation and Jochen Mayer for valuable inputs to the discussion. The services provided by MeteoSwiss, the Federal Office of Meteorology and Climatology, are much appreciated. This work was supported by Agroscope.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2024.109100.

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