University of Zurich[UZH]

The Impact of Climate Change on Crop Yields and the Effect of Potassium during Drought: An Analysis of the Long-Term Fertilization Experiment Demo in Zurich Affoltern, Switzerland

GEO 510 Master's Thesis

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List of abbreviation

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

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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 change on the yields of the most important crops. In this study, we report yields of wheat, barley, maize, potato and sugar beet from the long–term fertilization experiment Demo in Zurich Affoltern (Switzerland) and analyze their response to different climate variables (e.g., spring and summer temperature, precipitation, heat days, heavy rainfall). In addition, the impact of soil potassium (K) on the relationship of crop yields and precipitation was investigated. Rising summer temperatures have a negative impact on all crops, C_3 and C_4 plants in the Demo trial. Soil K only has a significant positive effect on maize yields in springs with low precipitation but no significant effect on the yields of other crops. No correlation could be found for the other crops. To maintain crop yields under further changing climate, farmers in Switzerland and Central Europe might implement less heat–sensitive species than wheat and potato. An alternative could be early–maturing maize varieties or crops, which grow early in the season such as barley. Barley is already a crop frequently used in drier areas and its resilience to changing climate was also shown in Central Europe and the current study, therefore its cultivation should be further considered. Further is a balanced supply of potassium important for maize to better resist drought stress, especially in spring seasons with little rainfall.

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 (Thornton et al., 2014; Olesen and Bindi, 2002). With climate change, temperature will rise and extreme events become more likely (Scherrer et al., 2016; Zubler et al., 2014). 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 (Bundesamt für Umwelt BAFU 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 (Bundesamt für Umwelt BAFU et al., 2020).

In Switzerland, the most important arable crops are wheat, barley, maize, sugar beet and potato (Federal Statistical Office, 2022). As C_3 plants, wheat, barley, sugar beet and potato have their temperature optimum at 20–25°C (Bonhomme, 2000), their yields are expected to be negatively affected by rising temperatures (Hawkins et al. 2013; Hijmans, 2003). In contrast to these crops, maize is a C_4 crop with a considerably higher temperature optimum (Sanchez 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 (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 (CH2018, 2018). As C_4 crops suffer more from drought stress than C_3 (Guidi et al., 2019) one can expect that maize is more susceptible to respond to decreasing summer precipitation with yield losses than other crops.

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 (Hasanuzzaman et al. 2018; Sardans & Peñuelas 2021; Wang et al. 2013). Various studies have shown the positive effect of sufficient K in soil in times of drought stress (Hasanuzzaman et al., 2018; Sardans & Peñuelas, 2015, 2021; Wang et al., 2013). Potassium also acts as an osmolyte and supports stomatal conductance in high temperature (Hasanuzzaman et al., 2018). It therefore plays an outstanding role in mitigating abiotic crop stress induced by climate change.

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 & Lorenzen, 1995), projective modelling (Chisanga et al., 2022; Trnka et al., 2004; Holzkaemper, 2020) 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 & 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 barley, maize, potato, sugar beet, wheat und grass cover ley grown in parallel. Confounding effects of seasonal weather conditions on plant performance typical of long–term experiments with crops grown in 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, as the majority of agricultural products are produced in this part of the country (Köllner et al., 2017). The study setup therefore facilitates the identification of species that should be preferably cultivated in Switzerland in the future. Through the different fertilizer scenarios, the effect of K on drought stress can be further analysed.

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

2. Materials & 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 9.4 °C and mean annual precipitation is 1050 mm (climate norm 1991–2010; MeteoSwiss, 2022). 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 1.4–1.7% and the soil pH (H_2O) varies between 6.7 and 7.9 among fertilization treatments (Figure Appendix 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 area 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 x 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 (Figure 1): Summer wheat (*Triticum aestivum*), sugar beet (*Beta vulgaris* subsp. *Vulgaris, Altissima Group*), maize (*Zea mays*), potato (*Solanum tuberosum*, winter barley (*Hordeum vulgare*) and two consecutive years of grass cover ley (with *Trifolium pratense*, *Trifolium repens*, *Dactylis glomerata*, *Festuca pratensis*, *Lolium perenne*, *Phleum pratense* L.). The 8 strips 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: PK (100% mineral P and K, 0% N), NP (100% mineral N and P, 0% K), NK (100% mineral N and K, 0% P), Zero (0% fertilization), Manure (25 t ha^{-1} yr^{-1} stable manure), NPK (100% mineral N, P and K), NPK+lime (100% mineral N, P and K and 2 t ha^{-1} yr^{-1} CaO) and Slurry (cattle slurry adjusted to 100% mineral N). Average nutrient inputs in the eight treatments are given in Table Appendix 2.

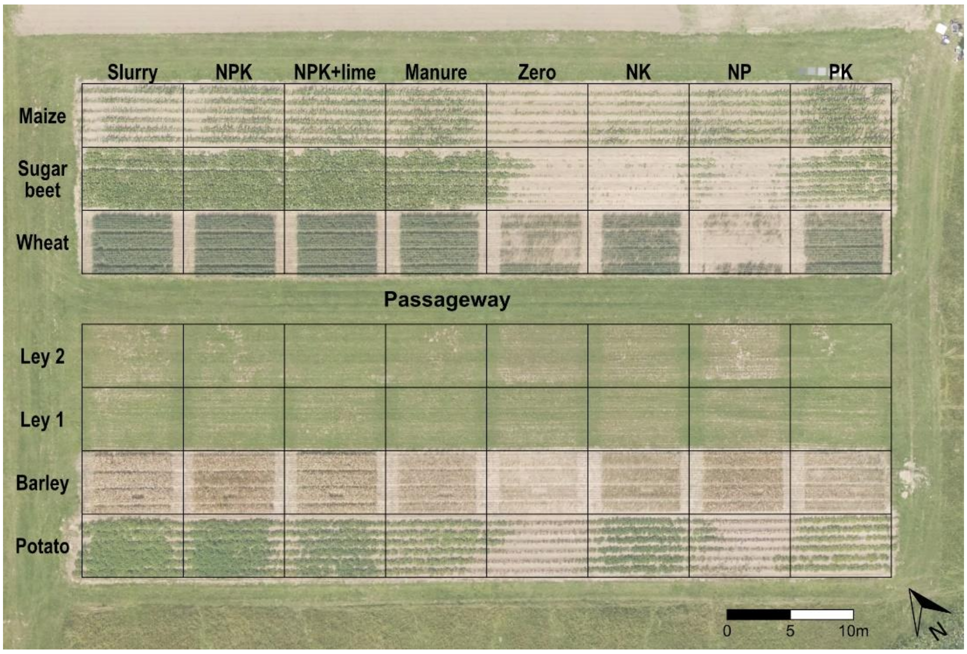

*Figure 1: **Design of Demo trial in 2020**. In rows there are the nutrition Slurry (cattle slurry adjusted to 100% mineral N), NPK (100% mineral N, P and K), NPK+lime (100% mineral N, P and K and 2 t ha^{-1} yr^{-1} CaO), Manure (25 t ha^{-1} yr^{-1} stable manure), Zero (0% fertilization), NK (100% mineral N and K, 0% P), NP (100% mineral N and P, 0% K) and PK (100% mineral P and K, 0% N). In lines are the different crops Maize, Sugar beet, Wheat, second year of grass cover ley (Ley 2), first year of grass cover ley (Ley 1), Barley and Potato. Each parcel is 5 x 8 m.*

Each crop was cultivated according to conventional soil management, comprising mouldboard ploughing to a maximum depth of 0.2 m and fertilization and plant protection according to the Swiss certification scheme Proof of Ecological Performance ("best agricultural practice"; Swiss Federal Council 2013). Each year, the main and by–products were sampled before harvest as grab samples (3 x 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 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) and soil K was reported as milligram K per kilogram dry soil [mg kg^{-1}]. As yield formation and fertilization effects are more complex in perennial mixtures than annual crops, the grass cover 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, 2022). 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 regression 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). Annual means were calculated for the months January to December. The variables from Table 1 were taken for the analyses.

*Table 1: **Climate variables, their abbreviation used in this study and respective units.** Variables and definitions according to MeteoSwiss.*

Climate variable	Abbreviation	Unit
Sum of precipitation year	Prec_yr	[mm]
Mean temperature year	Temp_yr	[°C]
Sum of precipitation spring	Prec_sp	[mm]
Sum of precipitation summer	Prec_su	[mm]
Mean temperature spring	Temp_sp	[°C]
Mean temperature summer	Temp_su	[°C]
Mean evapotranspiration spring	Evapo_sp	[mm]
Mean evapotranspiration summer	Evapo_su	[mm]
Sum of days with heavy rainfall (≥ 30 mm)[1] spring	Heavy_sp	[d]
Sum of days with heavy rainfall (≥ 30 mm)[1] summer	Heavy_su	[d]
Sum of heat days (max. ≥ 30° C)[1] spring	Heat_sp	[d]
Sum of heat days (max. ≥ 30° C)[1] summer	Heat_su	[d]

[1] Source: MeteoSwiss, 2022

2.3 Statistical analyses

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 to 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 of treatments were conducted with Tukey–adjustment of P–values.

Second, we selected 6 common variables that were used for the basic models for all crops since those variables are easy to reproduce and frequently used in other studies: “Prec_yr”, “Temp_yr”, “Prec_sp”, “Prec_su”, “Temp_sp” and “Temp_su”. We analysed their influence on yields with multivariate linear mixed effect 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. 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 & Strimmer, 2009).

Third, we used a stepwise function to analyse the parameters that have the greatest influence on the yield per crop. The model with the lowest Akaike information criterion (AIC) value was chosen and the variables of this stepwise model are output (Table 2). CAT–scores were calculated for this model, too.

To analyse the effect of soil K on yield response to precipitation, we used a linear mixed effect model with “Soil K” and “Precipitation” as interacting fixed effects and “Treatment” as random effect. 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 values between the minimum (2.5 mg kg^{-1} K) and maximum (35.7 g kg^{-1} K) of observed soil K 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 treshold soil K) and medium to high (treshold to maximum soil K) to estimate the slopes for those two groups.

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 with a significance level of $\alpha < 0.05$.

We used the R environment (R core team, 2022) for all calculations, statistical analyses and visualizations, in particular packages plyr and dplyr for data management (Wickham, 2011; Wickham et al., 2022), packages stats and lme4 for fitting simple linear and linear mixed effects models (Bates et al., 2015), packages psych, emmeans and Rcmdr for statistical analyses (Revelle, 2022; Lenth, 2022; Fox et al., 2022) and ggplot2 and ggpmisc for visualization (Wickham 2016; Aphalo 2022).

*Table 2: **Variables as fixed effects in the stepwise models**. Individual variables for each crop resulted out of the stepwise analyses.*

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

3. Results

3.1 Climate variables

The annual air temperature varied for the observation period (1990–2021) between 8.3 °C and 11.2 °C (Figure 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 the annual air temperature, summer (June – August) air temperatures increased by 1.5 °C over the last 30 years ($P = 0.005$; Figure 2). In opposite to summer and annual temperatures, spring (March – May) air temperatures 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 ($P < 0.001$; Figure 2). This was mainly connected to the number of heat days in summer ($P < 0.001$; Figure 2).

Mean annual precipitation averaged 1015 mm and varied between 750 mm and 1422 mm over the observation period (Figure 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 (≥ 30 mm) also varied among years. In summer, the days of heavy rainfall significantly increased by 1.5 days over the observation period ($P < 0.001$; Figure 2).

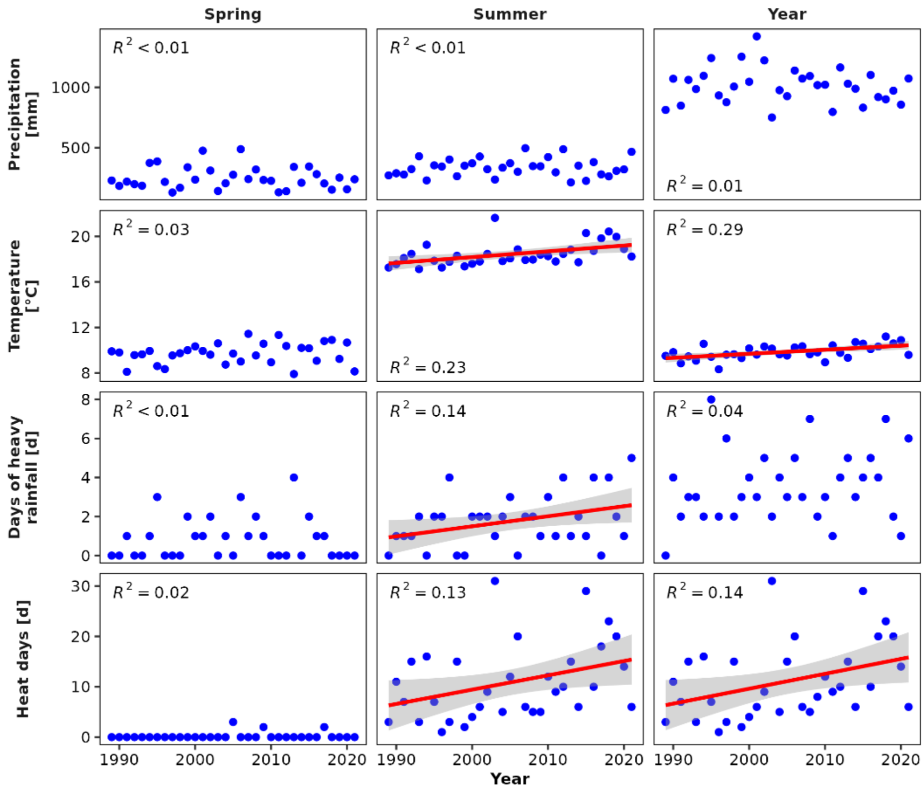

Figure 2: ***Climate variables in spring (March – May), summer (June – August) and the entire year (January – December) for the time period 1989 – 2021 in Zurich Affoltern.*** *Precipitation = Sum of precipitation in mm. Temperature = mean temperature in °C. Days of heavy rainfall = Sum of days with rainfall of 30 mm or more. Heat days = Sum of 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.*

3.2 Crop yields

Main crop yields of the reference fertilization treatment NPK averaged 3.9 t ha^{-1} (minimum – maximum: 2.0 – 5.7 t ha^{-1}) for wheat, 5.6 t ha^{-1} (3.5 – 8.0 t ha^{-1}) for barley, 10.9 t ha^{-1} (6.2 – 15.7 t ha^{-1}) for maize, 9.2 t ha^{-1} (4.9 – 13.9 t ha^{-1}) for potato and 19.9 t ha^{-1} (10.0 – 30.2 t ha^{-1}) for sugar beet (Table 3). Over the past 30 years, fertilization affected yields across all crops and led to significant yield reductions in all treatments except NPK+lime and Slurry when compared to the reference treatment NPK (Figure 3): Wheat showed the lowest yields for NP and Zero (both $P < 0.001$) than for NPK and intermediate yields for Manure, NK and PK (all $P < 0.001$). For barley, yields were significantly lower in Manure, NK, and NP (all $P < 0.001$) and lowest in PK and Zero (both $P < 0.001$; Figure 3). For maize, NP and Zero (both $P < 0.001$) had the lowest yields, while Manure, NK and PK were intermediate (all $P < 0.001$). Treatment differences were more diversified in potato, which had significantly lower yields in NK ($P < 0.001$), followed by Manure and PK (both $P < 0.001$), with lowest yields in NP and Zero (both $P < 0.001$; Figure 3). Sugar beet was the only crop with the highest yields in a treatment other than NPK, i.e., Slurry ($P = 0.140$). Compared to Slurry, NPK+lime ($P = 0.013$), PK ($P = < 0.001$)

and Manure (P = < 0.001) revealed lower yields, followed by NP ($P < 0.001$). Lowest yields were observed for NK and Zero (both $P < 0.001$).

Table 3: ***Dry matter yields of main products (barley, maize, wheat: grain; potato: tuber; sugar beet: beet) in t ha^{-1} for each crop planted in the reference fertilization treatment NPK averaged for the time period 1989 – 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)

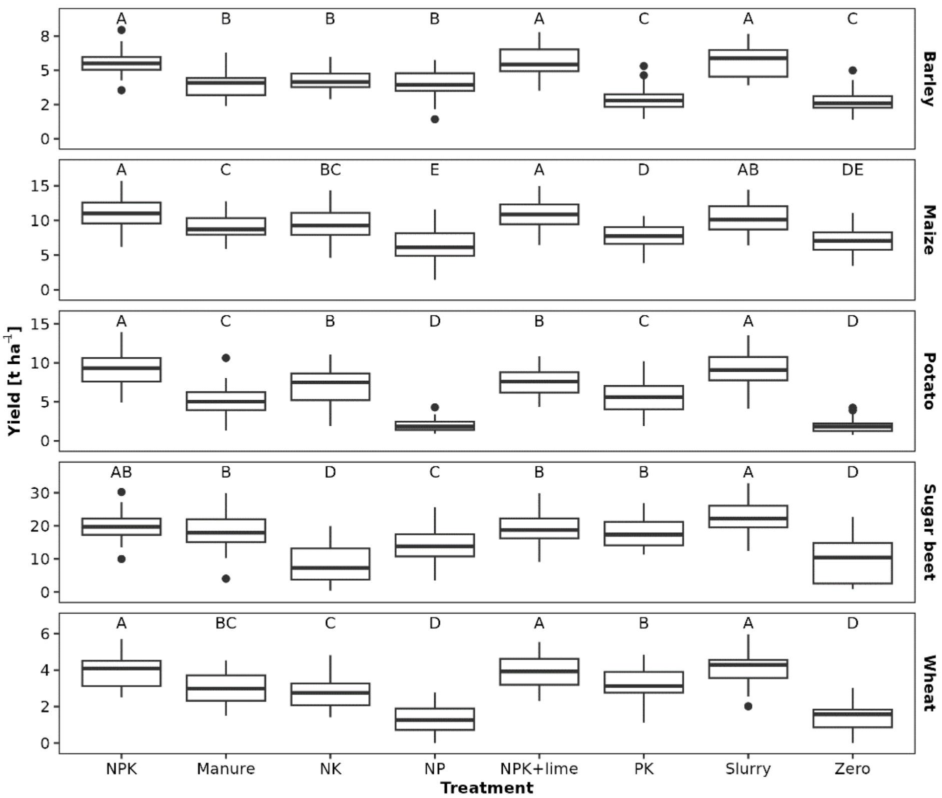

Figure 3: ***Crop yields of barley, maize, potato, sugar beet and wheat per treatment for the time period 1990 – 2021 in Zurich Affoltern*** *(n = 30 for barley, n = 31 for all other crops). The 8 treatments were fertilised with different organic and mineral fertilizers: PK (100% mineral P and K, 0% N), NP (100% mineral N and P, 0% K), NK (100% mineral N and K, 0% P), Zero (0% fertilization), Manure (25 t ha^{-1} yr^{-1} stable manure), NPK (100% mineral N, P and K), NPK+lime (100% mineral N, P and K and 2 t ha^{-1} yr^{-1} CaO) and Slurry (cattle slurry adjusted to 100% mineral N). Letters A to E describe the statistically significant different classes (treatments not sharing a letter within a crop have significantly different yields).*

3.3 Yield response to climate

The basic 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 (Figure 4). In general, summer temperature was negatively correlated to crop yields, although this effect was significant for maize, potato and wheat only (Figure 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 (Figure 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 basic models.

There was a negative relation between wheat yield and annual precipitation ($P = 0.002$) as well as temperature in summer ($P < 0.001$) according to the basic model (Figure 4). The stepwise analysis revealed the same negative relation of yield to annual precipitation ($P < 0.001$) and summer temperature ($P < 0.001$) and, in addition, to the number of heat days ($P = 0.005$; Figure 5).

The basic model showed that barley yield was significantly correlated to summer precipitation ($P = 0.021$; Figure 4). The stepwise analysis revealed significant positive relations of barley yield to evapotranspiration ($P < 0.001$) and precipitation ($P < 0.001$) in spring and days of heavy rainfall in summer ($P < 0.001$; Figure 5). Evapotranspiration in spring was by far the most important variable for barley yield (highest CAT score; Figure 5).

Maize yield was positively correlated to mean annual temperature ($P < 0.001$; Figure 4) but negatively to summer temperature ($P < 0.001$) and annual precipitation ($P = 0.016$) according to the basic model runs Mean annual temperature ($P < 0.001$) and precipitation ($P < 0.001$), respectively, were strongly positively and negatively correlated to maize yield as indicated by the stepwise model (Figure 5). Extreme events like heat days ($P < 0.001$) and days of heavy rainfall ($P = 0.006$) in summer negatively affected yields of maize.

According to the basic model, summer temperature had a negative influence on potato yield (Figure 4; $P < 0.001$). In the stepwise model, summer temperature had a strong negative relation to yield ($P < 0.001$). In addition, the stepwise model showed that precipitation in spring ($P = 0.002$; Figure 5) was negatively correlated to potato yields, whereas 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 ($P = 0.024$) were all positively correlated to potato yields.

Sugar beet yield was negatively correlated to spring precipitation ($P = 0.008$; Figure 4) according to the basic model. The stepwise model included heavy precipitation and evapotranspiration in spring (Figure 5), which were negatively (P = 0.031) and positively correlated to yields (P = 0.002), respectively.

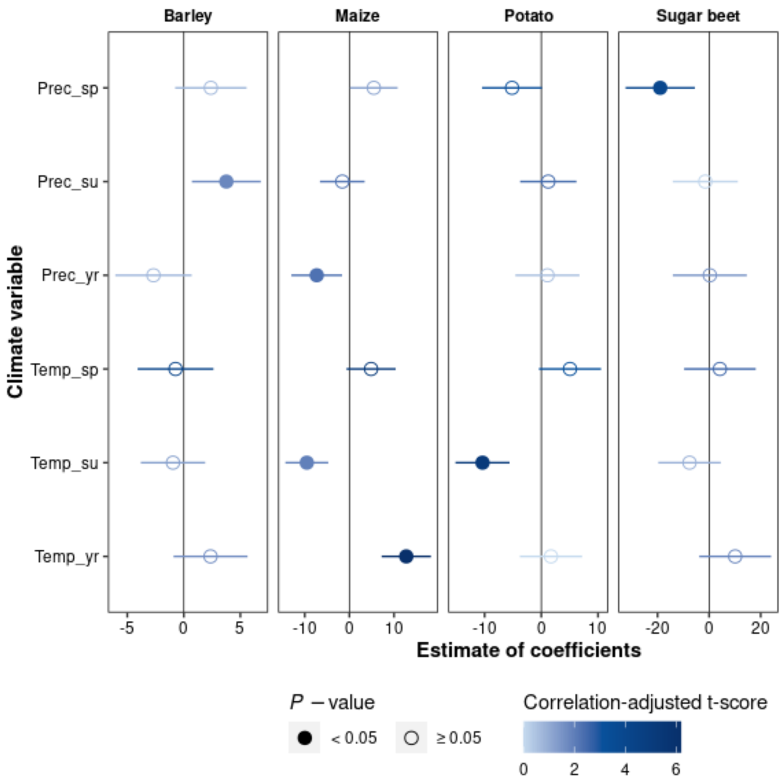

Figure 4: ***Coefficients (estimates and 95% confidence intervals) of the climate variables explaining crop yields in the basic model.*** *Climate variables are Sum of precipitation spring (March – May; Prec_sp), Sum of precipitation summer (June – August; Prec_su), Sum of precipitation year (January – December; Prec_yr), Mean temperature spring (Temp_sp), Mean temperature summer (Temp_su) and Mean temperature year (Temp_yr). They were included as fixed effects in linear mixed effects models with yield as response variable and treatment as random effect for barley (R^2= 0.09), maize (R^2= 0.44), potato (R^2= 0.44), sugar beet (R^2= 0.28) and wheat (R^2= 0.29). Significance and relative importance of coefficients are represented by P–values and CAT–scores (correlation–adjusted t–scores), respectively.*

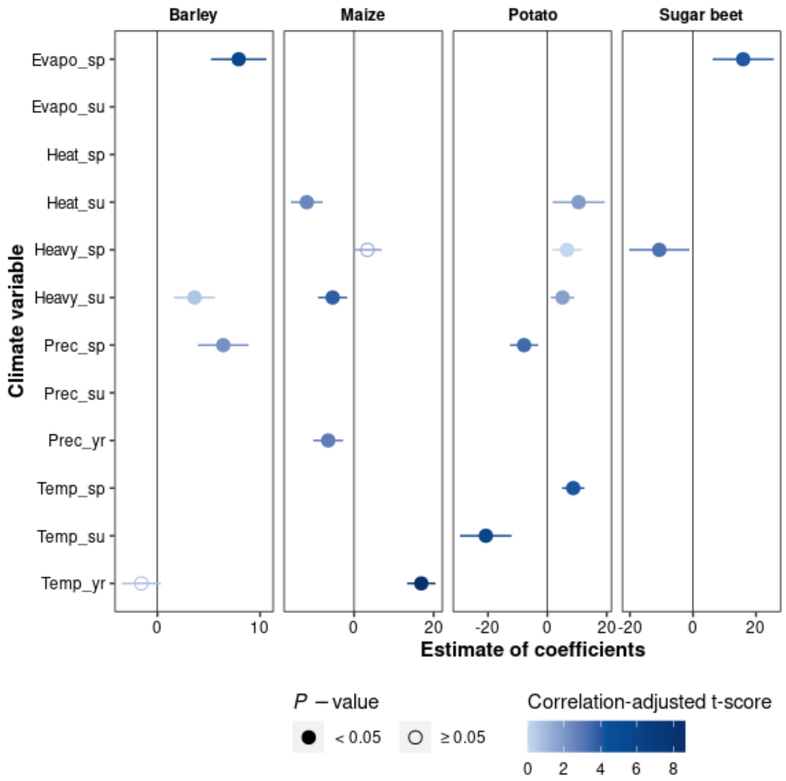

Figure 5: ***Coefficients (estimates and 95% confidence intervals) of the climate variables explaining crop yields in the stepwise model.*** *They were included as fixed effects in linear mixed effects models with yield as response variable and treatment as random effect for barley (R^2 = 0.32), maize (R^2 = 0.53), potato (R^2 = 0.51), sugar beet (R^2 = 0.28) and wheat (R^2 = 0.35). Variables per crop were chosen by stepwise analysis: Mean Evapotranspiration spring (March – May; Evapo_sp), Mean Evapotranspiration summer (June – August; Evapo_su), Sum of Hot days (max. ≥ 30° C) spring and summer (Heat_sp and Heat_su), Sum of days with heavy rainfall (≥ 30 mm) spring and summer (Heavy_sp and Heavy_su), Sum of precipitation spring and summer (Prec_sp and Prec_su), Sum of precipitation year (January – December; Prec_yr), Mean temperature spring, summer and year (Temp_sp, Temp_su and Temp_yr). Significance and relative importance of coefficients are represented by P–values and CAT–scores (correlation–adjusted t–scores), respectively.*

3.4 Yield response to precipitation under varying soil K

Maize was the only crop with a significant interaction of precipitation and extractable soil K 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 (Table Appendix 3). 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} (all slopes: *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 (≤ 7.0 mg kg^{-1}) soil K and medium to high (> 7.0 mg kg^{-1}) soil K (Figure 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 yields were reduced by approximately 1 t ha^{-1} per 100 mm reduction of spring precipitation (Figure 6). By contrast, the slope in the medium to high soil K group was not different from zero, indicating that maize yields were not affected by spring precipitation (Figure 6).

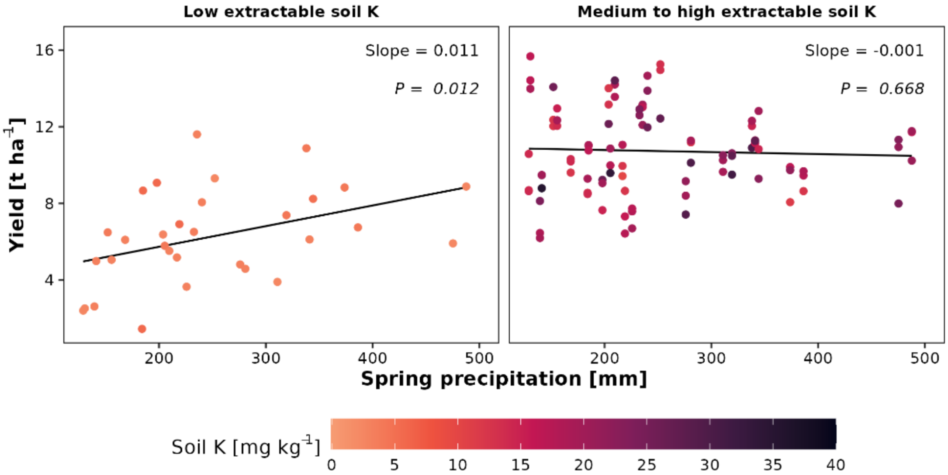

Figure 6: ***Yield of maize in relation to precipitation in spring (March – May) as affected by low (2.5 – 7.0 mg kg^{-1}) and medium to high (7.1 – 35.7 mg kg^{-1}) soil potassium (K) concentration for the time period 1990 – 2021 in the Demo trial in Zurich Affoltern.*** *Soil K concentration was measured in CO_2–saturated water in a ratio of 1:2.5 and atomic absorption spectrometry (Agroscope 1996).*

4. Discussion

4.1 Climate

During the period of time the Demo trial has been conducted, both annual and summer temperatures have been significantly rising 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 such as heat days and days with heavy rainfall. The same pattern applies to most of the meteorological stations across Switzerland (Scherrer et al., 2016). In contrast to temperatures, precipitation shows 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). This observation fits in the observation of Germany and other countries in Central Europe (Kaspar et al., 2017).

For Switzerland,three climate–change scenarios were created for its CH2018 climate report (CH2018, 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 7.3%, although with a high amount of uncertainty (-25.4% to +7.3%). Spring precipitation is projected to increase by about 6% (-0.7% to +18.7%). Therefore, trends for changes in precipitation are expected to be rather weak (CH2018, 2018). This is supported by our findings from the meteorological station at Zurich Affoltern over the past 30 years. In contrast to the precipitation, the CH2018 RCP4.5 scenario shows clear trend for temperatures and extreme events: Spring temperature are predicted to increase by 0.9 °C to 2.3 °C and summer temperature by 1.6 °C to 3.6 °C by the end of the century. It is expected that the frequency of heat days will also increase by 4 days per year (CH2018, 2018). Summer temperatures have already increased 1.5 °C over the last 30 years for the meteorological station at Zurich Affoltern. The number of heat days increased by 3 days per 10 years over the past 30 years in Zurich Affoltern, so the number increases faster as expected.

4.2 Crop yields

Wheat yields in the NPK treatment of the Demo trial (3.9 t ha^{-1}) were lower than both 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). In addition to Zero, NP is the treatment with the lowest yields, suggesting that K is the most limiting nutrient. Potassium is the key driver of processes governing plant–water–relations (Sardans & Peñuelas, 2021), which is especially important for summer crops that are metabolically most active when temperatures and evapotranspiration are high.

Barley yields in the NPK treatment of the Demo trial accounting for 5.6 t ha^{-1} correspond on average to yields observed in other agricultural trials across Central Europe (4.9 – 7.0 t ha^{-1}; Rötter et al., 2012; Panek & Gozdowski, 2021; Körschens, 1994). 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.

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; Huynh et al., 2019; van der Velde et al., 2012). Like wheat, maize is a summer crop and similarly affected by K deficiency in Zero and NP.

The average dry matter yield of potato in Demo (9.1 t ha^{-1}) was slightly 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 therefore 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 Zero and NP.

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 average yields in Germany and France (Řezbová et al., 2013; Bürcky & Winner, 1983). Apart from Zero, NK resulted in the lowest sugar beet yields. Phosphorus is highly immobile in 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 sugar beet makes this plant more prone to P deficiency than other crops (Bhadoria et al., 2002). In summary, crop yields in the Swiss Demo trial are within observed ranges of other Central European trials which suggests that the observations in the Swiss Demo trial are largely representative for Central Europe.

In the Demo trial, the treatments NPK and slurry produce the highest yields for all crops along with NPK+lime for barley, maize and wheat, which can also be seen in other fertilization experiments (Schmidt et al., 2000; Hülsbergen et al., 2001). This is the effect of optimal nutrient supply in these treatments (Richner et al., 2017). For sugar beet and potato, yields are significantly lower in NPK+lime than NPK and slurry. The increased pH value of the soil of 7.9 in NPK+lime may cause reduced boron availability (Barrow & 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). The manure treatment yields consistently lower yields for all crops compared with NPK and slurry, because of the low amount of applied mineralized N (Table Appendix 2) and, consequently, severe N limitation for the crops (Richner et al., 2017). In slurry, the amount of applied mineralized N is much higher (Table Appendix 2) as it is aligned with applied N in NPK according to Swiss agricultural practice (Richner et al., 2017). However, the amount of total N in slurry (Table Appendix 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 (Richner et al., 2017).

4.3 Impact of climate variables on crop yields

Wheat yields are negatively correlated with annual precipitation but not seasonal precipitation in the Demo trial. Potentially, higher precipitation, especially during winter, delays sowing 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 at the Demo site, it is difficult to predict 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 (CH, 2018). They did not only show a negative impact on wheat yields in the Demo trial, but the same was already observed in France (Brisson et al., 2010).

Barley shows high yields in years, when evapotranspiration is high in spring. As spring precipitation and temperature do not reveal a clear trend for the past 30 years, there is also no increase or decrease in barley yields. In general, the low R^2 values show that meteorological variables do not have a large effect on barley. Barley is able to adapt 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 & 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 (CH2018, 2018), we strongly assume that with optimal nutrient supply, barley is very likely to deliver reliable yields also in the Demo trial in the future.

In the Demo trial, maize yields have been positively influenced by rising annual and spring temperatures as the growing season has been extending and temperatures have come closer to the temperature optimum of 30–35 °C of the plant (Bonhomme, 2000; Sanchez 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 described to be susceptible to heat stress (Ceglar et al. 2018; Hawkins et al. 2013). In addition, we find negative effects of annual precipitation and the frequency of heavy rainfall events in summer on maize yields in the Demo trial. This is somewhat contradictory to projections for Switzerland, in which water scarcity between flowering and grain filling was found as one of the main climatic limitations for maize cultivation (Holzkämper et al., 2015). Both in Switzerland and Europe, 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 stress might be generally a minor issue in the Demo trial, up to now.

Potato yields are most strongly driven by climatic conditions, as underlined by the highest R^2 values of the model fits. Similar to maize, potato showed a negative correlation between temperature in summer and yield. Above 35°C, C_3 plants keep their stomata more closed and reduce photosynthesis (Bonhomme, 2000). Likewise affected by heat stress is tuber development, and hence, the amount and size of the harvested potatoes (Reynolds & Ewing 1989). Since summer temperatures will continue to rise, potato cultivation might become increasingly difficult in the Demo trial. In Europe, simulations of the effect of climate change on potato yields showed a decrease in yields by 15% to 19% until 2040–59 for Germany (Hijmans, 2003) but an increase of 5 to 25% for western Europe (Raymundo et al. 2018).

Sugar beet yields were negatively influenced by ample precipitation and heavy rainfall events in spring in the Demo trial throughout the last 30 years. Delayed sowing due to wet conditions in spring can negatively affect 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.

4.4 Potassium

There is no positive relation between precipitation and maize yields in the treatments with sufficient nutrient supply, i.e., NPK, NPK+lime and Slurry. Only for the treatment with distinct K deficiency can a positive relation between yield and precipitation 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 has also been shown by other studies around the world (Pettigrew, 2008; Aslam et al., 2012; Ul–Allah et al., 2020). As a C_4 plant, maize has a higher water use efficiency compared to C_3 plants due to the metabolic mechanism (Majeran et al., 2010). This is mainly related to the CO_2 concentrating mechanisms in photosynthetic metabolism (Downes, 1969). However, C_4 plants are more vulnerable to drought stress than C_3 plants, because the photosynthesis works close to the inflection point of the photosynthetic CO_2 response (Guidi et al., 2019; Wand et al., 2001). Under water limitation, the assimilation rate of CO_2 is lower in C_4 than C_3 plants, which is caused by a reduction of the photochemical efficiency of photosystem II and a lower linear electron flux (Guidi et al., 2019). Potassium regulates water transport in the plant and stomata activity. This is reflected by the positive influence of K supply in times of less precipitation for maize but not for the other 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, 2006), 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 in spring but not summer.

However, 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 (Bundesamt für Landwirtschaft, 2022) fall below that threshold. On the one hand, the main agricultural area in the Swiss lowland is situated on K–rich Cambisols (Veit & Gnägi, 2014). On the other hand, for soil K values of 12–30 mg kg^{-1} (and a clay content of 20–30%), normal K fertilization is recommended according to the Principles of fertilization of agricultural crops in Switzerland (PRIF 2017: Flisch et al., 2017) to replace crop K offtake. Yet, as the threshold of 7 mg K kg^{-1} soil can be considered as rather conservative due to the favorable site conditions regarding water availability, the true threshold is likely to vary with soil and landscape properties and might be much higher in individual situations. In order to prevent drought stress for arable crops, soil K values should be maintained according to the Principles of fertilization of agricultural crops in Switzerland (PRIF 2017: Flisch et al., 2017).

4.5 Suitability of 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. 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 (Tejera et al., 2019; Loughin, 2006). 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 experimental design.

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 realistic or even conservative for the average of Switzerland. Due to the proximity of the meteorological station (220 m), the influence of climate on crop yields can be estimated very accurately. We chose 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). Consequently, the seasonal weather influences on crop yields can be traced well.

The chosen crops belong to the most common arable crops in Switzerland (Federal Statistical Office, 2022) and the crop rotation is in line with federal proposals and common agricultural practice (Jeangros & 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 real replications are missing for the individual crops and fertilizations per year, the staggered design and the uniformiy of soil properties before the experimental start still provide meaningful outputs.

5. Conclusions

The evaluation of the crop yields of the Swiss Demo trial and the climate variables of the meteorological station at Zurich Affoltern showed that the yields of all investigated crops are negatively correlated with rising summer temperature. This refutes our hypothesis that maize would not or positively be influenced by increased temperature. Further, we assumed that spring precipitation is negatively correlated with cereal crop yields and summer precipitation is positively correlated with yields of potato, sugar beet and maize. However, the results of the Demo trial revealed a positive effect of spring precipitation for barley and no effect for wheat.

For summer precipitation, we could not observe any significant effect on yields of potato, sugar beet or maize. Our hypothesis, that K supply has a positive effect on yields of summer crops when precipitation decreases, could only be confirmed for maize but not for the other summer crops. And only for spring precipitation, we did not see any correlation for summer precipitation. Based on our analyses of yield response to climate conditions at one site and the future climate scenarios for Switzerland (CH2018, 2018), care should be taken to implement crop rotations with less heat–sensitive species than wheat and potato in the future. One solution might be to partly replace those crops with crops and / or varieties, which grow early in the season such as barley and rapeseed or early–maturing maize varieties. Further, alternative crops that are better adapted to high temperatures could be considered in the future. A balanced supply of potassium is important for maize to better resist drought stress, especially in spring seasons with little rainfall. According to the forecasts, these spring seasons with little rainfall will become less frequent. This study is one of a few long–term studies so far that shows that climate change adapted farming is essential for sustainable agriculture in Central Europe and Switzerland.

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Appendix

Figures

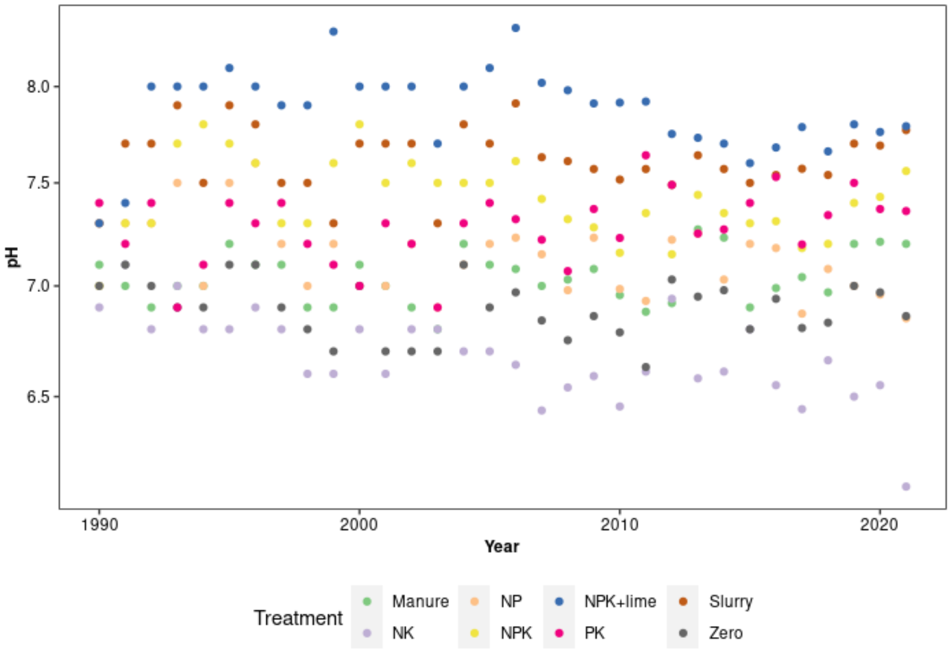

Figure Appendix 1: ***pH-value for every treatment over the time period 1990 – 2021 in Zurich Affoltern****.*

Tables

Table Appendix 1: ***Mean crop yields with standard error of wheat, barley, potato, maize and sugar beet in t ha^{-1} for the time period 1990 – 2021 in Zurich Affoltern.***

Crop	Slurry [t/ha]	Manure [t/ha]	NK [t/ha]	NP [t/ha]	PK [t/ha]	NPK+lime [t/ha]	Zero [t/ha]	NPK
Barley	5.6 ± 1.1	4.0 ± 0.9	4.3 ± 0.8	4.0 ± 1.0	2.9 ± 0.9	5.6 ± 1.0	2.8 ± 0.8	5.6 ± 1.0
Potato	9.2 ± 2.3	5.1 ± 1.9	7.0 ± 23	2.0 ± 0.8	5.6 ± 1.9	7.5 ± 1.7	2.0 ± 0.9	9.2 ± 2.1
Maize	10.2 ± 2.1	9.1 ± 1.8	9.5 ± 2.3	6.3 ± 2.4	7.7 ± 1.6	11.0 ± 2.1	7.1 ± 1.9	11.0 ± 2.3
Sugar beet	22.3 ± 4.8	18.2 ± 5.8	8.5 ± 5.7	14.1 ± 4.9	17.5 ± 4.4	19.3 ± 5.1	9.6 ± 6.7	20.0 ± 4.3
Wheat	4.0 ± 1.0	3.1 ± 0.9	2.7 ± 0.8	1.3 ± 0.7	3.1 ± 0.9	4.0 ± 0.9	1.4 ± 0.8	3.9 ± 0.9

Table Appendix 2: ***Mean nutrient inputs in kg ha^{-1} averaged over crops and years for the time period 1990 – 2021 in Zurich Affoltern.***

	Nmin [kg ha^{-1}]	**Ntot [kg ha^{-1}]**	**P [kg ha^{-1}]**	**K [kg ha^{-1}]**	**Ca [kg ha^{-1}]**	**Mg [kg ha^{-1}]**
NPK	120	120	103	328	0	0
Manure	12	103	64	130	76	130
NK	120	120	0	328	0	0
NP	120	120	103	0	0	0
NPK+lime	120	120	132	328	1117	328
PK	0	0	103	328	0	0
Slurry	103	209	71	315	191	315
Zero	0	0	0	0	0	0

Table Appendix 3: ***P-values of the effect of the interaction of soilK and precipitation on yields.*** *Years are included as random effects in the linear mixed model.*

	Spring	**Summer**
Wheat	0.433	0.419
Barley	0.257	0.126
Maize	0.043	0.611
Potato	0.471	0.149
Sugar beet	0.758	0.123

CRediT author statement

This Master's thesis is submitted in a slightly modified form as a manuscript to the journal "Agriculture, Ecosystems & Environment". For this reason, my supervisors have already viewed the thesis and helped me with the wording. Therefore, I am writing down the CRediT author statement below.

Jonathan Frei: Conceptualization, Methodology, Formal analysis, Writing - Original Draft, Visualization

Juliane Hirte: Supervision, Writing - Review & Editing, Conceptualization, Validation, Resources,

PD Dr. Guido Lars Bruno Wiesenberg: Supervision, Writing - Review & Editing, Conceptualization

Personal declaration

I hereby declare that the submitted thesis is the result of my own, independent work. All external sources are explicitly acknowledged in the thesis.

Zürich 14.07.2023 Jonathan Frei, 17-703-802