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Limited capability of organic farming and conservation tillage to enhance agroecosystem resilience to severe drought

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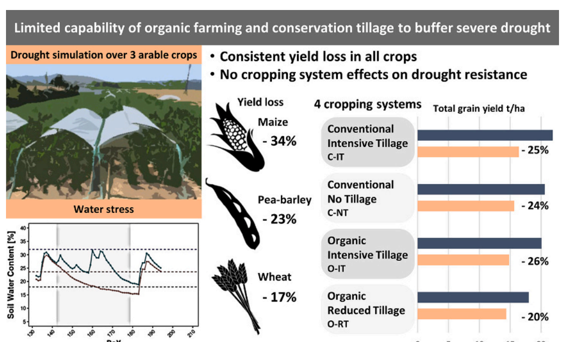
HIGHLIGHTS

- Drought was successfully simulated in three years and for three arable crops.
- Organic management and conservation tillage alone cannot buffer severe drought.
- Drought reduced yields of three crops grown in four common cropping systems.
- Drought limits the yield potential of high input cropping systems.
- Drought might result in low resource use efficiency and economic performance.

GRAPHICAL ABSTRACT



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ABSTRACT

CONTEXT: Climate change increasingly threatens food security, particularly through prolonged phases of drought. It is therefore important to evaluate and develop arable cropping systems with an enhanced capability to withstand severe drought events to ensure food production. However, it is still poorly understood whether specific management strategies, in particular organic farming and conservation tillage that are thought to be more resilient to drought, can enhance the ability of agroecosystem to withstand drought.

OBJECTIVE: The main objective of this study was, therefore, to test the ability of organic farming and conservation tillage practices to withstand drought within expected boundaries of climate scenarios for the end of the century.

METHODS: This study summarizes the effects of drought (both natural and experimental) on the productivity of three arable crops (maize, pea-barley mixture and winter wheat) assessed in three consecutive years in a long-term cropping system field experiment. We tested whether four relevant cropping systems (i.e., conventional and organic with and without soil conservation tillage) differ in their ability to reduce the impact of drought on plant

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yield and crop performance. We studied conditions of moderate natural drought (summer 2018) and severe experimental droughts using rainout shelters (3 years) after 8 years of contrasting field management.

RESULTS AND CONCLUSIONS: We found pronounced and consistent yield reductions due to experimental drought events for all cropping systems (34% for maize, 23% for pea-barley, and 17% for winter wheat). Drought induced yield reductions were largely similar across the four cropping systems, suggesting very limited capacity of any cropping system to buffer severe drought. Yet, there was an obvious but insignificant trend in maize in 2018 where under moderate and experimental drought conservation tillage resulted in a higher on-average yield compared to the plowed systems. Furthermore, drought resulted in lower nitrogen (N) uptake by the crops and a positive N budget, which could result in higher N losses after a drought period.

SIGNIFICANCE: This study demonstrates that drought has consistent and adverse effects on crop productivity under conventional, organic and soil conservation arable cropping. It further demonstrates that it is difficult to find effective adaptation strategies for arable systems under realistic future scenarios and underlines the need to combine all available practices, from soil management to crop and cultivar choice, to mitigate drought impacts on crop productivity.

1. Introduction

Agriculture faces climate change in two ways. First, it contributes directly to the emissions of greenhouse gases and, second, it is directly impacted by changes in extreme weather and climate events, impairing agricultural productivity (IPCC, 2022). Although moderate climatic changes, such as increasing temperature and elevated CO_2 concentration, could also present opportunities for agricultural production in some places (i.e., prolonged growing seasons, extended cropping areas; (Holzkämper et al., 2014)), negative impacts might dominate in wide regions across Europe. Particularly prolonged phases of drought (Olesen et al., 2011) and the increase of compound extreme events (i.e. joint extremes of multiple climatic variables) are expected to lead to negative consequences (Trnka et al., 2014; CH2018, 2018). Recent examples, such as the co-occurrence of heat waves and droughts in 2003, 2011/2012, 2015 and 2018, have revealed considerable impacts on agricultural production in large parts of Europe, including Switzerland (Ciais et al., 2005; Zahradníček et al., 2015; Ionita et al., 2017; Brunner et al., 2019b). Not only productivity but also other important aspects of agroecosystems might be negatively impacted by drought, particularly nutrient use efficiency or water cycling and water quality, enhancing environmental impacts of agriculture (Klages et al., 2020; Zarrineh et al., 2020).

Arable cropping systems therefore need to be evaluated and developed for their capability to withstand drought and ensure food production. Multiple strategies exist, which potentially support the drought resistance of arable crops, for example organic farming (Lotter et al., 2003) or conservation agriculture (Steward et al., 2018). Both strategies are shaped towards increasing soil quality (Mäder et al., 2002) and were shown to enhance ecosystem multifunctionality, particularly by improving the delivery of supporting and regulating services (Snapp et al., 2010; Stavi et al., 2016; Wittwer et al., 2021). However, it is still not clear to which extent these changes in crop management increase the adaptation to drought.

Drought-related losses in crop production might be lower under organic compared to conventional farming because productivity and thus water use are generally lower in most organic systems (Ponisio et al., 2015; Schärer et al., 2022). Furthermore, soil organic carbon (SOC) concentrations are often higher (Gattinger et al., 2012; Büchi et al., 2022) and plant symbionts more abundant in organic cropping systems (Banerjee et al., 2019), potentially contributing to improved soil aggregation (Loaiza Puerta et al., 2018), water retention (Pimentel et al., 2005) and, thus, to drought resistance.

Conservation tillage, spanning from reduced to no tillage, might further support drought resistance because reduced soil disturbance stabilizes the soil structure by aggregate formation (Loaiza Puerta et al., 2018), improves water holding capacity and infiltration, and is generally coupled with improved soil cover by plant material (mulches) that reduces evaporation (Holland, 2004). Additionally, conservation tillage might also better conserve soil carbon stocks as compared to intensive tillage under both conventional (Ogle et al., 2019) and organic (Krauss et al., 2022) management.

The impact of drought and its interaction with the respective cropping system is likely to vary among different crop species, especially among different plant functional types such as cereals vs. legumes or C3 vs. C4 plants, as well as among crop growing periods (winter vs. summer crops; (Cohen et al., 2021). Although studies on such interactions are still rare, drought responses of crops growing in different cropping systems suggest species-specific reactions (Sun et al., 2021; Sun et al., 2022), requiring a broad range of crop species to be assessed (Penna et al., 2020). Furthermore, crop-specific management practices are most likely impacted differently by drought. For example, liquid manure fertilization, i.e., slurry, might still increase soil N availability under drought, while granulate mineral fertilization is useless if precipitation is completely missing. However, studies testing whether different cropping systems vary in their ability to buffer against drought are rare and mainly compare two different cropping systems (Steward et al., 2018; Kundel et al., 2020; Cohen et al., 2021). Moreover, studies that compare four different cropping systems over multiple years and with different crops are completely missing. Such studies are needed to obtain a robust answer about the resilience of different cropping systems and to properly predict whether specific cropping systems can help to reduce the negative impact of drought for future food security.

Two approaches are commonly used to study the effects of drought on ecosystems: i) experiments manipulating precipitation, e.g., using rainout shelters, and ii) comparisons among years with either natural drought or normal "wet" periods. Experimental drought is often used to simulate rather extreme events (in terms of rainfall exclusion), while a natural drought is usually less distinct, but also more variable and unpredictable. Thus, the combination of moderate (natural) and severe (experimental) drought will be particularly helpful to explore how different cropping systems are able to buffer future drought events (Kroel-Dulay et al., 2022).

In this study, we investigated the effects of severe experimental drought on the productivity of three different arable crops (maize, pea-barley mixture, and winter wheat) in three consecutive years in a long-term cropping system field experiment in Switzerland. We specifically tested whether four important arable cropping systems (i.e., conventional and organic with and without soil conservation tillage) differ in their ability to buffer drought effects on the three crops. We hypothesized that organic farming and conservation tillage enhance the resistance to drought.

2. Methods

2.1. Experimental site and cropping systems

This drought experiment was conducted at the FArming System and Tillage long-term experiment (FAST) of Agroscope, which compares important arable cropping systems in Switzerland and Europe, i.e., conventional and organic farming with each two types of tillage intensity (conservation vs. intensive tillage; (Wittwer et al., 2021). The field site is located in an undulating landscape near Zurich (latitude 47°26′ N, longitude 8°31′ E). The soil type at the experimental site is a calcareous Cambisol that contained on average 1.4% soil organic carbon (SOC), 23% clay, 34% silt, 43% sand, and had a pH(H_2O) of 7.3 when the experiment was started. The temperate climate has a long-term average annual precipitation of 1054 mm and a mean annual temperature of 9.4 °C (1981–2010; (MeteoSwiss, 2022).

The FAST experiment follows a staggered start design with two similar field trials that were established next to each other on the same parcel. The first trial (called FAST I) was started in summer 2009 and the second trial (called FAST II) in summer 2010. In Swiss conventional farming, synthetic fertilizers and pesticides are allowed and frequently used for crop nutrition and protection, while in organic farming both practices are prohibited. The conventional systems are managed according to the "Proof of Ecological Performance" (PEP) guidelines of the Swiss Federal Office for Agriculture. The PEP guidelines need to be followed to receive any agricultural support payments and their standards are based on the concept of integrated production. Thus, guidelines require a balanced nutrient budget and a regulated crop rotation (Swiss Federal Council, 2004). The organic cropping systems are shaped following the "Bio Suisse" guidelines that are compulsory for organic producers all over Switzerland (Bio Suisse, 2020). Both FAST trials comprise the following cropping systems: conventional with intensive tillage (C-IT), conventional with no tillage (C-NT), organic with intensive tillage (O-IT), organic with reduced tillage (O-RT). These four cropping systems are replicated four times in each trial and contains two subplots (size 3 m × 5 m), one with the drought treatment and a control receiving ambient rainfall, following a split plot design (Fig. S1).

The four cropping systems of the FAST experiment follow the same 6-year crop rotation including major arable crops for Switzerland, i.e., winter wheat, maize, grain legumes (field beans in the first crop rotation cycle and pea-barley in the second cycle), winter wheat and 2 years temporary ley (grass-clover mixtures). Drought simulations were conducted during the second crop rotation phase from 2017 to 2019 with three different crops in three consecutive years on the same plots in FAST I, cultivated with maize (2017), a pea-barley mixture (2018), and winter wheat (2019), and additionally in 2018 in FAST II on plots cultivated with maize (field operations are listed in Table S1).

2.2. Drought simulations

Our drought treatment aimed to simulate severe drought, as summer precipitation (June–August) is projected to decrease up to 25% by 2060 and up to 38% by 2085 according to the climate scenarios for the Canton of Zurich (CH2018, 2018). Drought periods were set to induce severe drought events, according to crop critical stages and field management restrictions (Table S1). We used tunnel-shaped shelters (3 m × 5.5 m) covered with a transparent and ultraviolet light transmissible plastic foil (Gewächshausfolie UV5, 200 μm, Folitec Agrarfolien-Vertrieb) to exclude precipitation (Fig. 1). Neighboring control plots (i.e., open field conditions) received actual ambient precipitation. Shelters were open at both ends as well as at both sides and had a ventilation opening of 35 cm over the entire length at the top to stimulate air circulation and avoid temperature or humidity increase underneath the shelters. The height of the shelters was adjustable to be at least 20 cm higher than the crop canopy. We did not monitor aboveground climatic variables, such as air temperature, relative humidity or photosynthetically active radiation, but these were shown to only marginally differ from ambient conditions in a previous study using the same shelter system (Hofer et al., 2016) and more generally with similar shelter systems (Kundel et al., 2018; Hunter et al., 2021). The rainout shelters were placed on the outer part of each main plot, adjacent to the grass strips between blocks. This was done to divert the retained precipitation collected by the shelters away from the plots to avoid water input by runoff (Fig. S1). The factor combination of cropping system and drought resulted in eight treatments with four replicates per crop-year combination (Fig. S1).

2.3. Measurements

2.3.1. Pedo-climatic data

Soil water content (SWC, EC-5, Decagon Devices Inc., Pullman, WA, USA) was continuously recorded at 10 and 40 cm soil depths with two replicates per treatment (blocks B and C) in FAST I. Data were averaged at 10 min intervals by data loggers (CR1000 and CR216, Campbell Scientific Ltd., Loughborough, UK). During 2018 in FAST II (maize), SWC at 20 cm was recorded weekly with the same sensor (EC-5, Decagon Devices Inc., Pullman, WA, USA) connected to a portable data logger (ProCheck, Degagon Devices Inc., Pullman, WA, USA) in each subplot ($n = 4$ per treatment, FAST II). SWC was averaged on a daily basis for further processing. SWC curves were computed for each experimental year using the average of the 10 and 40 cm SWC data for FAST I and using the data at 20 cm for FAST II to estimate SWC over 0–40 cm depth for each crop-year combination (Fig. S2).

In addition, we characterized the water stress severity for each cropping system, drought treatment (subplots with ambient precipitation and under experimental drought using rainout shelter), and crop-year combination, by calculating (i) the duration of water stress, and (ii) water deficiency. To do so, we first calculated the plant available water (Reynolds et al., 2009), i.e., the difference between water content at field capacity (FC = SWC at Ψ −100 hPa) and wilting point (WP = SWC at Ψ −1500 hPa), and second, we defined a critical threshold (CR) of 40% plant available water content. We used cropping system specific values for the water content at field capacity and at wilting point assessed at 10 and 40 cm soil depth from intact soil core samples (n = 4 per plot, 0.05 m diameter, 0.05 m height; approx. 10^{-4} m^3 volume) taken in 2017 in the same plots (Table S2). All undisturbed soil cores were saturated from below and equilibrated to the matric potential of −100 hPa on ceramic suction plates for the determination of soil porosity and volumetric water content at field capacity. Residual water content at −1500 hPa was determined on smaller undisturbed samples (0.01 m height by 0.05 m diameter) in PVC rings subsampled from two of the four cores due to the time requirement for this measurement.

Fig. 1. Rainout shelter on (A) maize, (B) pea-barley mixture, and (C) winter wheat.

Finally, all cores were oven-dried at 105 °C for at least 24 h and weighed for bulk density determination.

Duration of water stress was defined as the cumulative number of days when SWC was below the critical threshold (Fig. S3). Water deficiency was defined as the time integrated SWC below that threshold (the area below CR), which considers both duration of water stress and water deficit (Fig. S3). This allowed us to look at overall effects of water stress severity over all crop-year combinations including actual ambient precipitation pattern and experimental rain exclusion.

In order to contextualize our drought simulation, we additionally modelled SWC during the period from 1990 to 2020 for our study location. We used daily meteorological data from the nearby MeteoSwiss station, Zürich/Kloten (KLO, 47.48° N, 8.54° E; (MeteoSwiss, 2022) and a model using the FAO-56 dual crop coefficient method (Allen et al., 2005) with standard values for a grass reference crop to predict evapotranspiration. Site specific measured values, i.e., the mean over all cropping system, were used for total porosity (0.49), field capacity (0.32) and permanent wilting point (0.187). Using the same threshold of 40% of plant available SWC (corresponding to 24% SWC *v/v* for the field site), we then assessed the number of days with critical SWC for plant uptake for the entire 30-year period (1990–2020, Fig. S5) similarly as for the SWC field measurements.

2.3.2. Crop data

Total aboveground biomass and grain yield as well as weed biomass were harvested at crop maturity inside a 1.5 m × 1.5 m frame within the inner area of the drought subplots and subplots receiving ambient precipitation to avoid border effects. After harvesting, grains were threshed and fresh weights of grain and straw were recorded. Then, all plant materials were oven-dried at 60 °C for 48 h until constant weight, and dry weight was recorded. Weed biomass was directly dried at 105 °C for 30 h for dry weight determination. Grain and straw samples were finally milled and analyzed for N concentrations.

To assess the impact of drought on nutrient use efficiency, we calculated the N budget of each crop as the difference between N input and N output based on a surface model calculation not accounting for soil N content and dynamic. A positive N budget reflect N surplus and a negative N budget suggest soil N depletion. N input includes total N applied as fertilizers (mineral and organic), N fixed by legume symbionts (pea crop) and atmospheric deposition (15 kg/ha/y). N fixation of pea symbionts was estimated after Anglade et al. (2015) as follows:

Nfix = (4 + 0.66 * Nyield/havest index) * 1.3.

N output consisted of the N content in harvested (grain) and exported products (wheat straw). Average N applied as fertilizer as well as grain and straw yield and N content are presented in Table S3. We took the average over all crops to look at the N budget over the whole crop sequence (maize, pea-barley, wheat) after averaging the maize 2017 and 2018 data.

2.4. Statistical analyses

All statistical analyses and figures were generated with R in RStudio (version 4.2.1; (R Core Team, 2020). Linear mixed models were used to test the effects of cropping systems and drought treatment on crop variables, with the function lmer() from the R package 'lmerTest' (Kuznetsova et al., 2015). 'Cropping systems (CS)' and 'drought treatment (D)' were treated as fixed factors with interactive effects between 'CS' and 'D' (CS × D). 'Main plot' within 'blocks' was included as random factor in the models to account for the split-plot design (1|Block: Mainplot). In case of significant cropping system main factor effects, a post-hoc test (Tukey) was performed with the function emmeans() from the package 'emmeans'. In the case of maize, an additional analysis considering both cropping periods (2017 and 2018) was performed, including 'year' as additional fixed factor in the model and its interactions with CS and D. This allowed us to compare the effect of the natural drought in 2018 to our experimental droughts in 2017 and 2018.

To assess the overall effects of drought in relation to the reduction in precipitation, we finally performed a linear mixed model between the duration of soil water stress and soil water deficiency (number of days under critical SWC and time integrated SWC deficit, respectively) and yield with 'crop-year' as random factor. In order to remove intrinsic yield level differences among crops, we calculated the relative yield of each crop as the ratio between recorded yield over Swiss reference yields determined for conventional crop management (Sinaj et al., 2017). The function emtrends() from the package 'emmeans' was used to compare the slopes of the cropping systems against zero and between each other. The same procedure was applied to test how the reduction in precipitation compared to the norm period affected SWC deficiency (the area of SWC curves below 24% SWC *v/v* during experimental drought periods).

3. Results

3.1. Weather conditions and experimental drought simulation

In this study, crops faced both a natural drought as well as experimental drought. Compared to the norm period (1981–2010), actual ambient precipitation during the three main crop growing periods (i.e., from sowing to harvest of the respective crops) was about 20% lower for maize in both years (2017 and 2018), 45% for the pea-barley mixture in 2018, and 9% for winter wheat in 2019 (Table 1). June 2018 even had the lowest precipitation recorded in the last 30 years (MeteoSwiss, 2022) and resulted in SWC being under the critical plant available water threshold also in control plots (Fig. S2). Therefore, this natural drought in 2018 (Brunner et al., 2019b; Gharun et al., 2020) provided an ideal opportunity to study the effect of natural versus experimental drought. Natural drought was tested by comparing maize data for 2017 (a year without a clear drought) and 2018 (with a natural drought).

Rainout shelters successfully excluded precipitation in the drought subplots and resulted in a constant decrease in SWC during the experimental periods in all crop-year combinations (Fig. S2). Although not analyzed statistically (due to low number of replicates), no pronounced

Table 1
Precipitation, study set-up and precipitation scenarios from NCCS (Swiss National Centre for Climate Services) for the study location (MeteoSwiss station, KLO, 47.48° N, 8.54° E, mean annual precipitation (1981–2010) = 1053 mm).

	Maize 2017	Maize 2018	Pea-Barley 2018	Wheat 2019
Annual precipitation (mm)	918	902	902	972
Crop growing period precipitation (mm)	May-Sep	May-Sep	Mar-Jul	Oct-Jul
Norm period (1981–2010)	538	538	495	857
During experiment	431	418	272	776
% change to norm period	*−20*	*−22*	*−45*	*−9*
Experimental drought				
Set up shelter	11.07.2017	03.07.2018	22.05.2018	25.04.2019
Remove shelter	15.09.2017	20.09.2018	28.06.2018	19.06.2019
Number of days with shelter	66	79	37	55
Number of excluded rain events (> 1 mm)	30	21	11	25
Precipitation excluded (mm)	188	242	88	204
Precipitation excluded (mm/day)	−2.9	−3.1	−2.4	−3.7
Predicted changes in precipitation (mm/day) for the respective crop growing period				
NCCS climate scenarios:	May-Sep		Mar-Jul	Oct-Jul
2085 - RCP2.6 - lower estimate	−2.8		−0.9	−1.1
2085 - RCP8.5 - lower estimate	−4.1		−1.1	−1.1

differences in average SWC values were noticeable between the different cropping systems. However, systems with conservation tillage showed a slight tendency towards better conserving SWC (lower water deficiency) with increasing reduction in precipitation among study years and drought treatments (Fig. S5).

For maize (2017 and 2018), experimental drought excluded an average of 3 mm/day (July–September; Table 1), which corresponds to the RCPs (Representative Concentration Pathways) scenarios 2.6 (concerted climate change mitigation efforts) and 8.5 (no climate change mitigation) lower estimates for the horizon 2060 and 2085 of the Swiss National Centre for Climate Services (CH2018, 2018). For pea-barley (2018) and winter wheat (2019), the rain exclusion during the respective cropping periods resulted in 2.4 and 3.7 mm/day, respectively, which was higher than the projected absolute changes in precipitation (Table 1).

3.2. Effects on productivity

The rain exclusion resulted in significant yield losses in all crops and cropping systems, with average grain yield reductions of 34% for maize (36% in 2017 and 33% in 2018), 23% for pea-barley, and 17% for winter wheat (Fig. 2, Table S3). No significant interactions between experimental drought and cropping systems were detected in any of the crop-year combinations, indicating that all cropping systems were affected to the same extend by drought with pronounced negative impact on yield. Significant cropping system effects on yield were observed for maize in 2017 and winter wheat in 2019 (Fig. 2) irrespective of drought treatment, with conventional intensive tillage (C-IT) generally having the highest yield and organic reduced tillage (O-RT) generally having the lowest yields.

Maize grain yield ranged from 5.9 to 13.0 t/ha (Table S3) and was strongly impacted by drought in both years, but reacted differently to cropping systems among years (Fig. 2). In 2017, systems with intensive tillage (C-IT, O-IT) resulted in significantly higher productivity, whereas the organic reduced tillage system (O-RT) had the lowest productivity (Fig. 2). In 2018, systems with conservation tillage (C-NT, O-RT) showed higher maize yields, irrespective of the drought treatments (Fig. 2). Yet, this obvious trend was not significant under our experimental setup. However, when comparing only the control subplots with ambient precipitation in 2017 and 2018, it is remarkable that both systems with intensive tillage (C-IT, O-IT) suffered strongly from the natural drought event in 2018, with a yield reduction of 4 t/ha (31%) and 2 t/ha (18%) under conventional and organic management, respectively (Fig. 2). In contrast, the conventional no tillage system (C-NT) could maintain its yield (1% lower) under this natural drought while the maize yield was even 1 t/ha (9%) higher in 2018 for the organic system with reduced tillage (O-RT). This is supported by a significant year-cropping system interaction (F $value_{3,36} = 8.7$, p value <0.001) when analyzing both maize years together.

Total pea-barley grain yield ranged from 2.5 to 4.4 t/ha (Table S3) and was significantly affected by the drought treatment, but not by cropping systems. This response was driven by the pea yield which

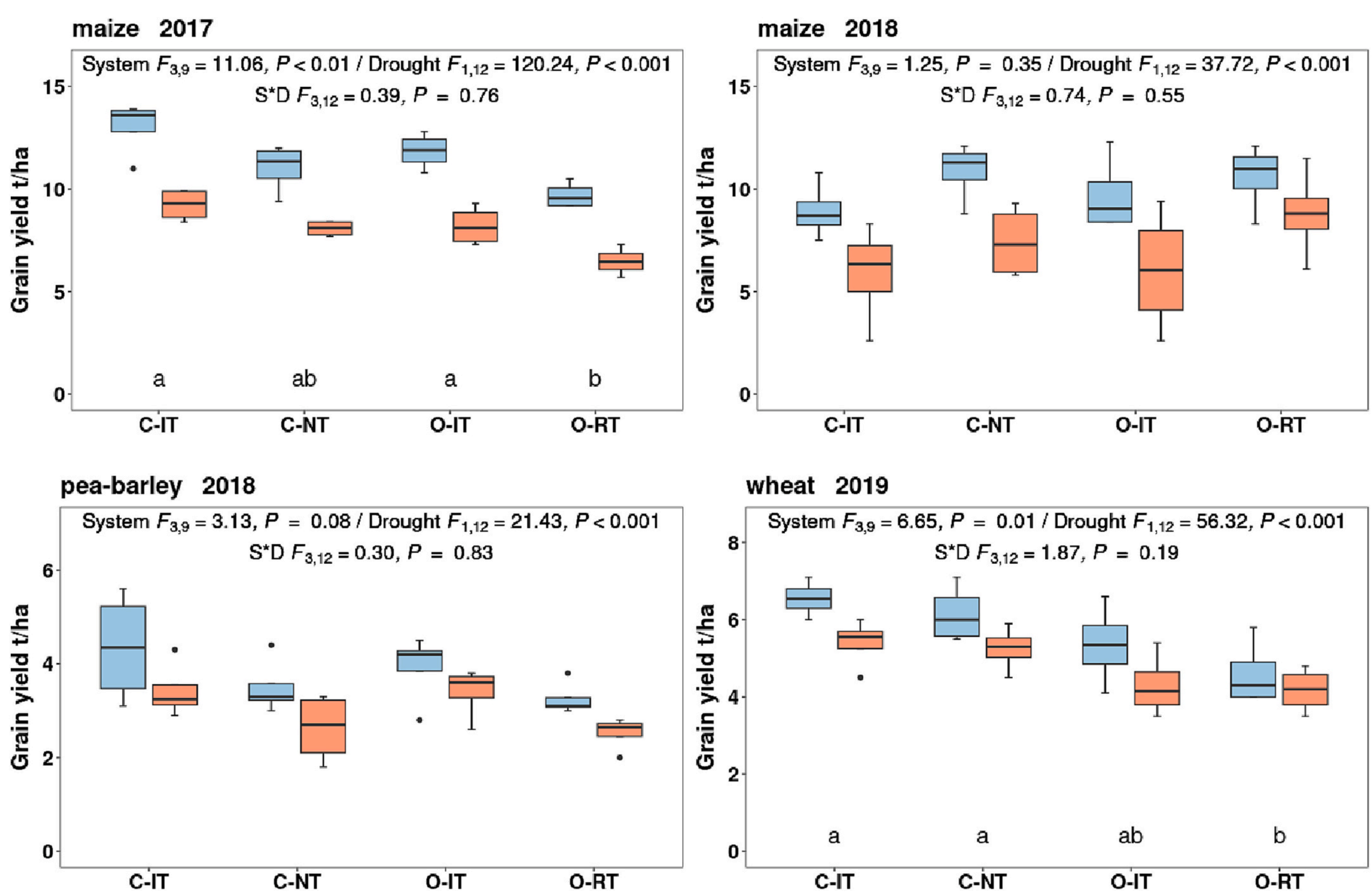

Fig. 2. Grain yields of maize, pea-barley mixture and winter wheat under ambient precipitation (blue) and exposed to experimental drought using rainout shelters (red); $n = 4$, C-IT: Conventional intensive tillage, C-NT: Conventional no tillage, O-IT: Organic intensive tillage, O-RT: Organic reduced tillage. Boxplots display the median (horizontal line), the 25th and 75th percentiles (colored box), the minimum and maximum (whiskers), and outliers (points). Statistical outcomes of the linear mixed models for the effects of fixed factors, cropping systems and drought, and their interaction are displayed ($F_{df1,\ df2}$ value with df1 = numerator degrees of freedom and df2 = denominator degrees of freedom). Letters indicate significant differences among cropping systems (Tukey post-hoc test). Note the different ranges of the y-axes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

dominated the mixture with overall 68% of the total yield (Fig. S6). The proportion of pea grain yield of the total pea-barley yield was significantly affected by the drought treatment (F $value_{1,12} = 11.2$, p value <0.01) and decreased from 74% without drought to 59% with drought. In contrast, barley yield was significantly higher in systems with intensive tillage (C-IT, O-IT), but was not directly impacted by the drought treatment (Fig. S6).

Winter wheat yield ranged from 4.2 to 6.6 t/ha (Table S3) and was impacted both by cropping systems and drought (Fig. 2). Productivity in both conventional systems (C-IT, C-NT) was significantly higher than in the organic system with reduced tillage (O-RT).

Weed biomass was generally higher in organic compared to conventional cropping systems, except for the pea-barley mixture in which no specific weed control operations were conducted, neither under conventional nor organic management. Drought only reduced weed biomass in maize (only in 2017 and for the organic system with reduced tillage in 2018), and not in the other crops (Fig. 3). Except for maize in 2018, no significant interactions between cropping systems and drought were found, similar to the findings for grain yields.

Whereas the N budget under ambient precipitation was mostly balanced in the different cropping systems (around 0), drought resulted in increased N budgets, i.e., lower N use by the crops (N input > N output), resulting in N surplus (positive values; Fig. 4). In general, N budgets were higher for both organic systems receiving cattle slurry which contains less N in mineral forms than conventional systems (Fig. 4). This between-system difference, however, does not necessarily indicate higher potential N losses in organic systems but a slower release of N as organic N-rich compounds first need to be degraded to become plant available.

3.3. Resistance to drought

To assess whether the investigated cropping systems showed some adaptive capacities to resist against drought, we tested the absolute yield loss and the relationship between yield and soil water stress among all crop-year combinations. In general, absolute yield losses were not significantly different among cropping systems for any crop (maize 2017: $F_{3,12} = 0.4$, $P = 0.76$; maize 2018: $F_{3,12} = 0.7$, $P = 0.55$; Pea-Barley 2018: $F_{3,12} = 0.3$, $P = 0.80$; wheat 2019: $F_{3,12} = 1.9$, $P = 0.19$, Fig. 5). Nevertheless, absolute yield losses across all crops (all crops: $F_{3,60} = 1.3$, $P = 0.30$) tended to be smallest in systems with conservation tillage (RT or NT), particularly under organic management (O-RT: -1.5 ± 0.35 t/ha, C-NT: -2.0 ± 0.4 t/ha, O-IT: -2.2 ± 0.49 t/ha, C-IT: -2.2 ± 0.43 t/ha; mean ± standard error, $n = 16$; Fig. 5).

The relationships between the duration of soil water stress, expressed as the number of days under critical SWC, and relative yield over reference yields for Switzerland, showed that both systems with intensive tillage (C-IT, O-IT) could not sustain their yield potential under drought stress, i.e., with increasing number of days under water stress (Fig. 6). Both systems with intensive tillage showed significant negative relationships between soil water stress and relative yield (C-IT: $p < 0.001$, O-IT: $p < 0.01$). In contrast, yields of the organic system with

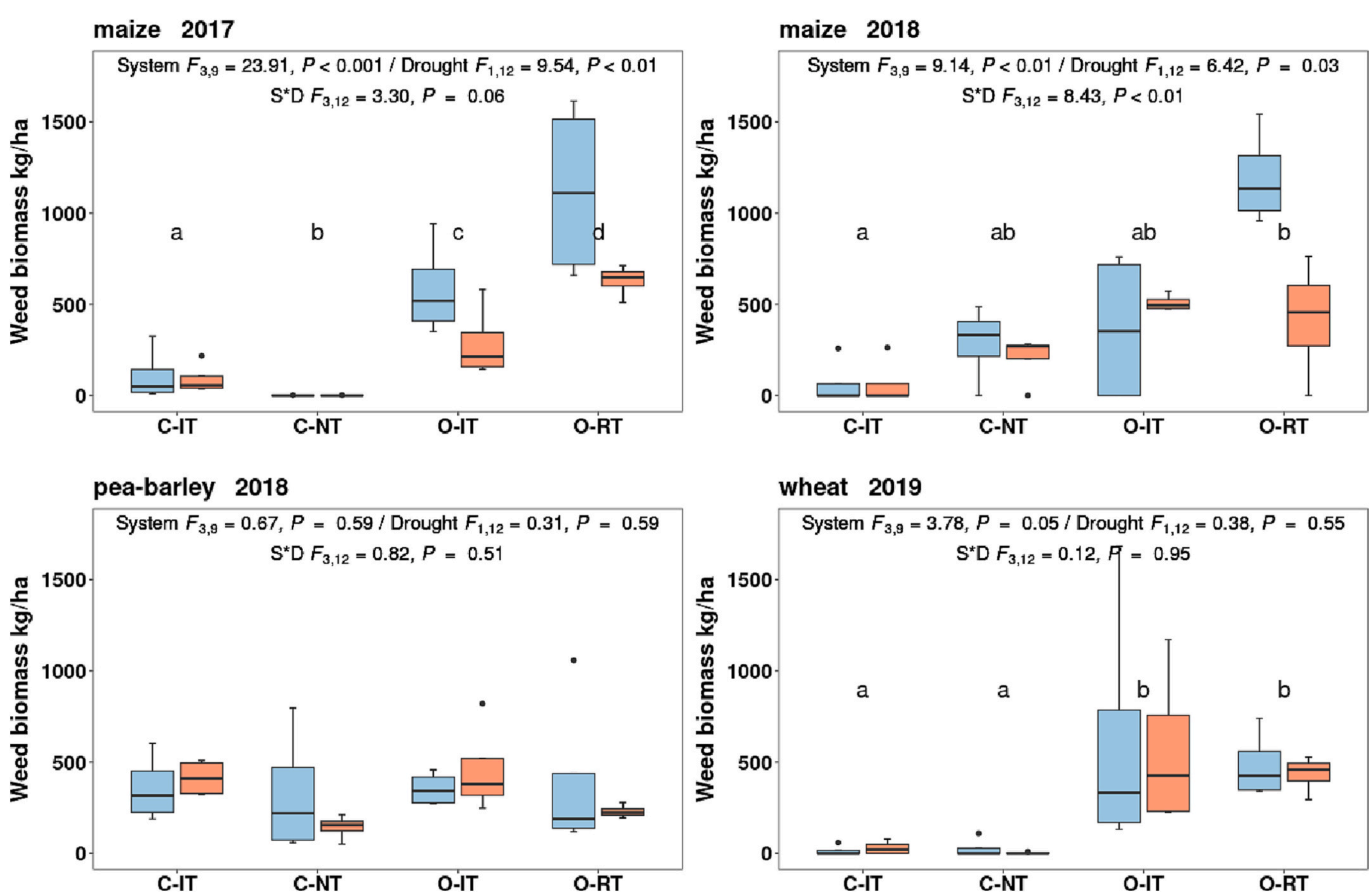

Fig. 3. Weed biomass of maize (2017 and 2018), pea-barley mixture and winter wheat under ambient precipitation (blue) and exposed to experimental drought using rainout shelters (red); $n = 4$, C-IT: Conventional intensive tillage, C-NT: Conventional no tillage, O-IT: Organic intensive tillage, O-RT: Organic reduced tillage. Boxplots display the median (horizontal line), the 25th and 75th percentiles (colored box), the minimum and maximum (whiskers), and outliers (points). Statistical outcomes of the linear mixed models for the effects of fixed factors, cropping systems and drought, and their interaction are displayed ($F_{df1, df2}$ value with df1 = numerator degrees of freedom and df2 = denominator degrees of freedom). Letters indicate significant differences among cropping systems (Tukey post-hoc test). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

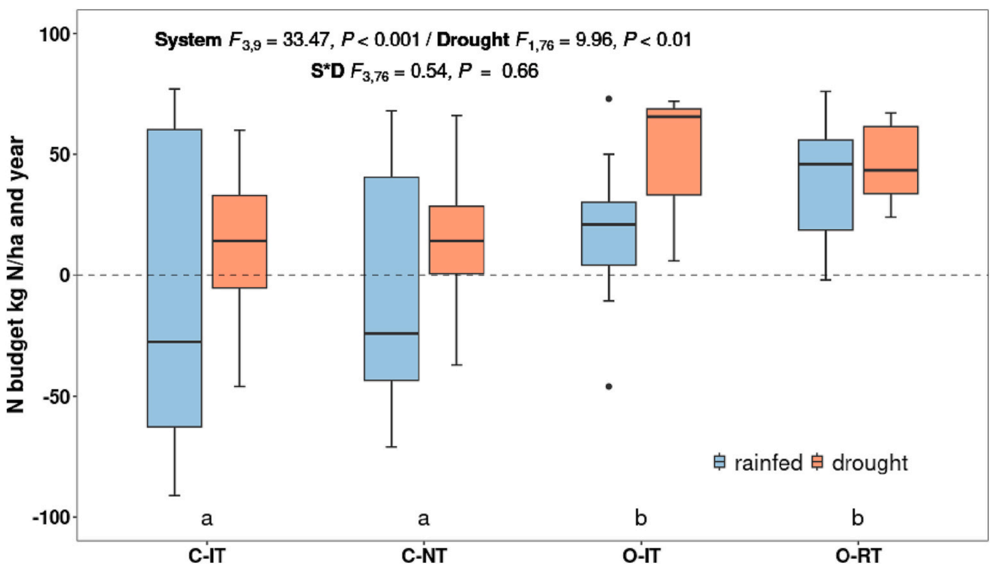

Fig. 4. N budget (N input by fertilizer or N fixation by pea symbionts minus N output as exported products in kg N/ha) over the three-year crop rotation with maize, pea-barley mixture and winter wheat under ambient precipitation (blue) and exposed to experimental drought using rainout shelters (red); n = 4, C-IT: Conventional intensive tillage, C-NT: Conventional no tillage, O-IT: Organic intensive tillage, O-RT: Organic reduced tillage. Boxplot displays the median (horizontal line), the 25th and 75th percentiles (colored box), the minimum and maximum (whiskers), and outliers (points). Values above zero indicate N surplus, while values below zero indicate soil N depletion, i.e., N output being higher than N input. Statistical outcomes of the linear mixed models for the effects of fixed factors, cropping systems and drought, and their interaction are displayed ($F_{df1,\ df2}$ value with df1 = numerator degrees of freedom and df2 = denominator degrees of freedom). Letters indicate significant differences among cropping systems (Tukey post-hoc test).

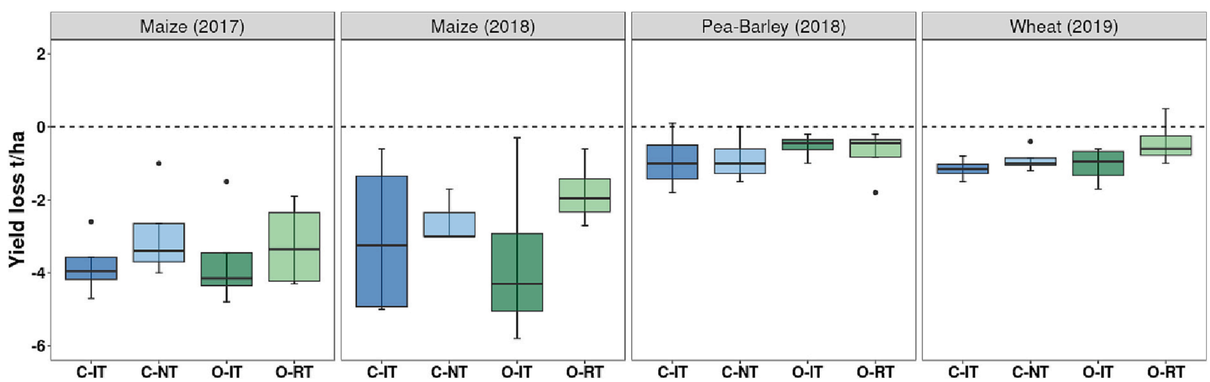

Fig. 5. Absolute yield change between plots under ambient precipitation and exposed to experimental drought using rainout shelters for each crop-year combination and the four cropping systems; n = 4, C-IT: Conventional intensive tillage, C-NT: Conventional no tillage, O-IT: Organic intensive tillage, O-RT: Organic reduced tillage. Boxplot displays the median (horizontal line), the 25th and 75th percentiles (colored box), the minimum and maximum (whiskers), and outliers (points). No significant cropping system effects were detected in any crop.

reduced tillage (O-RT) did not show a significant relationship with soil water stress (Fig. 6, $p = 0.15$), indicating no significant yield reduction with increasing drought stress, however, at very low levels (always below reference yields). Similarly, the slope of the conventional no tillage system (C-NT) was not significant (Fig. 6, $p = 0.09$), but still more negative than O-RT. A very similar overall pattern was observed when water stress severity was expressed as water deficiency, i.e., as time integrated SWC below critical threshold (Fig. S7).

4. Discussion

Drought is a major cause of yield loss worldwide (Bänziger and Araus, 2007), and projections of decreasing precipitation and increasing evaporative demand will further exacerbate losses in many regions (IPCC, 2022). It is predicted that overall water scarcity will also increase in Switzerland (Brunner et al., 2019a), even if the occurrence of extreme events is spatially variable and depends on site conditions and regional water use (Brunner et al., 2019b). Our study confirms that drought has a major impact on yield of maize, winter wheat, and pea-barley mixture, within expected scenarios for the end of the century. Yet, we did not find strong interactions of cropping systems with drought, indicating that severe drought effects are similar in organic, conservation and conventional agriculture.

4.1. Cropping system responses to experimental drought

A range of studies have shown that organic, conventional and conservation agriculture have a major impact on crop yield and further ecosystem services, often mediated via the soil (Pittelkow et al., 2015; Ponisio et al., 2015; Wittwer et al., 2021). However, to date, the effect of drought on arable crop yields in interaction with different long-term agricultural management systems has been only poorly studied for arable crops in temperate regions. Based on the many beneficial effects of less intensive cropping systems, we expected that cropping systems implementing soil conservation practices, such as conservation tillage (C-NT, O-RT), the application of organic amendments or avoiding the use of synthetic fertilizers and pesticides (O-IT, O-RT), will also reduce the negative effects of drought on crop performance, due to the well-known increase of overall soil quality (Mäder et al., 2002; Kundel et al., 2020) and related soil processes such as water infiltration and retention. Thus, organic and conservation agriculture are often expected to reduce the negative effect of drought on crops.

Many important soil functions are driven by soil organisms and their diversity (Wagg et al., 2014), which are directly impacted by

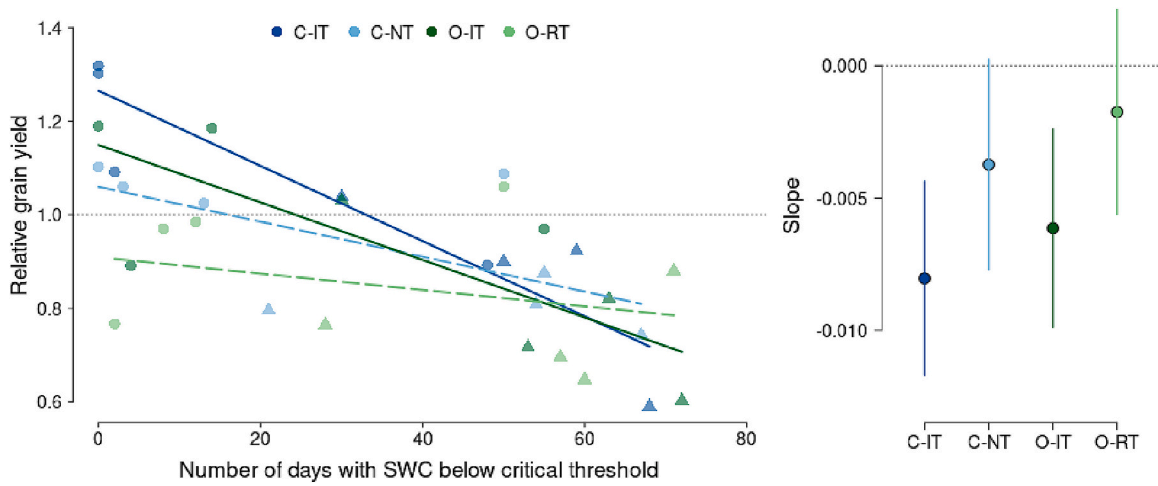

Fig. 6. Left panel: Linear regressions (dashed line if not significant, $p > 0.05$) for each cropping system and all crops between soil water stress (section 2.4.1, Fig. S3), during the drought simulation periods under ambient precipitation (points) and exposed to experimental drought using rainout shelters (triangles), and mean relative yield over reference yields for all crops (section 2.5). Right panel: Slopes of the linear regressions with confidence intervals (CIs). Slopes are significant ($p < 0.05$) if the CIs are not overlapping with zero, i.e., for C-IT and O-IT. C-IT: Conventional intensive tillage (dark blue), C-NT: Conventional no tillage (light blue), O-IT: Organic intensive tillage (dark green), O-RT: Organic reduced (light green). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

agricultural management (Hartmann et al., 2015; Hartman et al., 2018). The resistance of soil functions to drought is critical to regulate water and nutrient cycles (storage and supply) helping to sustain productivity. Recent studies under comparable conditions have found that organically managed fields generally harbor higher soil biota abundance and diversity (Banerjee et al., 2019; Kundel et al., 2020) and sustain more functions than conventionally managed fields. This suggested that organic farming could provide a buffer against drought (Birkhofer et al., 2021; Meyer et al., 2021), even if drought conditions directly and negatively affect soil biota and their activity (Birkhofer et al., 2021). Within the FAST experiment, all three soil improving cropping systems (C-NT, O-IT and O-RT) showed higher abundances and diversity of soil biota compared to the conventional intensive tillage system (C-IT; Wittwer et al., 2021), i.e., increased earthworm abundance, mycorrhizal fungi abundance and diversity. However, in our study, over three years and three different arable crops, we found pronounced negative effects of experimental drought on productivity for all four cropping systems. Similarly, within the same experiment, litter decomposition was also strongly impacted by drought for all three crops, with no differences among the four cropping systems (Liu et al., 2022). Thus, against our expectations, we did not find any significant differences in the adaptive effects of the investigated cropping systems on crop yield under severe drought conditions, despite differences in soil quality.

Further, soil characteristics beyond soil biology, such as soil texture, have been shown to influence the critical soil moisture threshold for plant water stress (Fu et al., 2021) and the capacity of cropping practices, e.g., conservation tillage, to buffer against drought (Steward et al., 2018). Moreover, drought intensity and duration might also influence the capacity of cropping system to sustain productivity as shown again for conservation agriculture systems losing their greater resistance to moderate drought when drought becomes under more extreme conditions (Steward et al., 2019). At our site, different cropping systems resulted in differences in soil properties, such as bulk density, total porosity, as well as water holding capacity (Wittwer et al., 2021; unpubl. data). However, we observed little change in SWC among cropping systems and lastly no significant interactions between cropping system and drought for most studied crops. The impacts of the experimental drought on crop performance were obviously larger than these beneficial effects of soil characteristics. Indeed, although SOC was shown to be important for drought resistance (Renwick et al., 2021), cropping practices induced changes of SOC are low, such as for tillage (Dimassi et al., 2014; Mary et al., 2020). Even if some SOC increase was observed within the experiment under reduced tillage (Krauss et al., 2022), the redistribution of SOC in the top soil might not influence water availability in deeper layer under severe drought.

The impacts of drought on crop growth and productivity are complex and depend on many aspects such as timing, site conditions and crop species. For example, drought was shown to have stronger effects on crops when it happened during the reproductive phase of the plants (Cohen et al., 2021). In our study, drought was also simulated during the reproductive phase of the crops (e.g., Mai-June for wheat and pea-barley and August for maize). For maize, the experimentally excluded precipitation corresponded nicely to the projected changes in local climate. For pea-barley and winter wheat, we targeted our experimental drought period on the respective critical crop stages, which resulted in reduced precipitation during spring as these crops are already ripening in June and July. Although reduction in precipitation in Switzerland is projected to occur mainly in the summer months, data from the last 30 years show that spring drought events were also observed and became more frequent in recent years in terms of duration and intensity (Fig. S4).

Our results lastly indicated that although cropping systems with conservation tillage could not buffer the severe drought impacts, these systems could reduce the productivity loss under moderate natural drought. Indeed, both systems with conservation tillage, i.e., conventional no tillage (C-NT) and organic reduced tillage (O-RT), could maintain maize yield during the natural drought in 2018 compared to 2017. Particularly the organic system with reduced tillage resulted in the lowest absolute yield loss. The generally higher soil quality in the organic reduced tillage system (Wittwer et al., 2021; Krauss et al., 2022) might still have helped sustaining productivity under drought. However, higher weed pressure and N limitation restricted the yield potential of this system under current ambient conditions (Cooper et al., 2016), which brings challenges in expanding organic reduced tillage systems to secure food production. Our results also show that although no-tillage might better conserve soil moisture, soil water is not necessarily available for plants. Root growth and water uptake might be impaired by higher bulk density and lower porosity in this system. Thus, we need a better understanding of soil processes and the relationships between soil water retention, root growth and plant water uptake (e.g., Sun et al., 2022) in order to design cropping systems with a high drought resistance for a drier future.

4.2. Crop responses to simulated drought

Despite a lack of an overall effect of cropping systems on drought resistance, the crops studied here displayed interesting different patterns in response to drought. When subjected to the experimental drought, both pea and barley shifted their water uptake patterns to shallower depths without niche differentiation in any of the cropping systems (Sun et al., 2022). However, during the natural drought in 2018, only barley showed this behavior, suggesting higher drought tolerance of legume crops and thus advantages of mixtures containing legumes for adaptation to moderate droughts (Hofer et al., 2016; Sun et al., 2021). On the contrary, winter wheat could increase water uptake from deeper soil layers under drought (Sun et al., 2022), suggesting that winter crops with an established root system could react to spring drought. Indeed, the lowest yield losses were observed in this winter crop. This suggests that although cropping systems were indeed able to change some soil properties and affected hydraulic traits of some crops (Sun et al., 2022), cropping systems did not affect root water uptake patterns under severe drought. Overall, these findings imply that plant ecophysiology exerted a larger impact on crop performance under drought than soil quality.

4.3. Enhancing cropping system resistance to drought

There are different strategies currently being discussed to design more drought resistant cropping systems (Debaeke et al., 2017). One of them is crop breeding. However, grain yield and drought adaptation are complex genetic traits, which will result in relevant gains to be rather slow (Bruce et al., 2002; Rogger et al., 2021). Thus, beside crop genetics, it is important to identify other cropping practices that can enhance drought resistance of cropping systems with already available cultivars.

Cropping system diversification in time (i.e., crop rotation) and space (i.e., crop mixture) has been shown to generally exhibit greater resilience in the face of drought (Degani et al., 2019; Renwick et al., 2021; Sanford et al., 2021). In our study, crop species diversity was identical in all four cropping systems (same crop rotation), potentially narrowing the range of responses to drought. Moreover, in Switzerland, conventional systems are already geared towards integrated production, reducing the potential of different adaptive capacities between organic vs. conventional cropping systems. This could also partly explain the lack of significant cropping system effects on drought adaptation, which could have been clearer under more contrasting management, such as continuous intensive mono cropping over time, i.e., without crop rotation as mandatory in Switzerland. Thus, replicating our study design in other regions with different regulatory schemes and different farming systems will show if the impact of cropping systems is indeed smaller than the impact of drought severity.

While crop yields are often seen the major ecosystem service from cropping systems, other services need to be addressed as well when designing more resistant cropping systems to make food systems more climate-smart. We observed that differences in productivity by cropping system occurred mostly under ambient precipitation and disappeared under severe drought. This suggests that drought limited the yield potential of high-input cropping systems, translating to lower resource use efficiency (N and water) and lower economic performance (Schmitt et al., 2022), but also to higher environmental externalities such as increased N losses (Zarrineh et al., 2020) compared to normal climatic conditions. Indeed, within the same experiment, soil nitrate availability was strongly reduced during the experimental drought periods in the pea-barley mixture and in winter wheat (Liu et al., 2022). But soil nitrate concentrations increased rapidly with incoming precipitation, confirming the risk of higher N losses when plants are not able to take up flushes of quickly mineralized N (Liu et al., 2022). Here, we also observed lower N uptake by drought-stressed crops, resulting in N surplus (positive N budget) in all cropping systems. This might be particularly problematic in conventional systems with high application rates of mineral N fertilizer, which is retained less in the soil matrix compared to organic forms of N as applied in organic agriculture (Frick et al., 2022). Thus, N fertilization schemes should be adjusted to plant N needs in a drier future, further increasing the demand for precision agriculture.

5. Conclusions

In this study, we successfully simulated severe drought events over three years for three different arable crops within expected boundaries of climate scenarios for the end of the century. We found strong negative impacts of prolonged drought on all crops studied and for all four cropping systems after 8 years of contrasting management. Thus surprisingly, we found only marginal adaptive capacity of organic management and conservation tillage to mitigate such drought impacts. However, the projected increasing frequency of such extreme events in the future will lead to lower productivity levels which need to be compensated, especially in face of a growing population.

Increasing the extent of cropping areas is not possible in most countries without converting natural or semi-natural areas to intensive cropping areas, with potentially high environmental externalities. Thus, efforts to adapt current or design new cropping systems to and for a drier future must include other solutions for crop production such as adapted cultivar and crop species choices, enhanced use of crop mixtures, influencing microclimatic conditions to reduce evaporative demand, water-saving practices, or sustainable irrigation strategies. However, the risks of low resource use efficiency, low economic performance, and high negative environmental impacts of intensive cropping systems clearly demand not only focusing on crop production alone but call for a fundamental change in our food systems.

Declaration of Competing Interest

None declared.

Data availability

Data will be made available on request.

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Author contributions

RW: Managing the field experiment, setting up the drought simulation, collecting and processing plant and soil samples, installing and maintaining soil sensors, data processing and analysis, writing the manuscript.

VK: Supported setting up the drought simulation and assisting in field work, contributing to data analysis and discussion, revising the manuscript.

EO: Setting up the drought simulation, collecting and processing plant and soil samples, installing and maintaining soil sensors, revising the manuscript.

QS: Setting up the drought simulation, collecting and processing plant and soil samples, installing and maintaining soil sensors, processing soil moisture and soil temperature data, revising the manuscript.

YL: Setting up the drought simulation, collecting and processing plant samples, revising the manuscript.

AKG: Supported setting up the drought simulation and assisting in field work, contributing to data analysis and discussion, revising the manuscript.

NB: funding acquisition, designing the experiment, scientific discussions, revising the manuscript.

MvdH: funding acquisition, initiation of the FAST experiment, designing the experiment, scientific discussions, revising the manuscript.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2023.103721.

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