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Reduced plant water use can explain higher soil moisture in organic compared to conventional farming systems

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ABSTRACT

Conventional high-input farming systems in Europe are often regarded as unsustainable with severe environmental impacts on biodiversity, soils, water and climate. Low-input farming approaches, such as organic farming, have been proposed to reduce environmental impacts while further improving soil properties such as soil organic matter content and aggregate stability. Whether these changes also influence ecohydrological properties and improve the water relations of organically grown crops remains unclear. In this study we assessed the long-term effects of conventional and organic farming systems on the water relations of soils and crops in the "DOK" (bio-Dynamic, bio-Organic & 'Konventionell' = conventional) trial. In particular, we tested if organic and conventional farming lead to marked differences in soil moisture, soil water evaporation, as well as root water uptake depth and stomatal conductance of winter wheat and soybean during the growing seasons 2017 and 2018. Stable isotope analyses and ecophysiological measurements revealed that organic compared to conventional farming did not affect soil water evaporation or root water uptake depths. Instead, we found higher soil moisture in the rooting zone and reduced stomatal conductance (g_s) in organically grown wheat. Treatment effects on soil moisture and g_s of soybean were smaller but showed similar tendencies as observed in wheat. Also, leaf area, and grain and straw yield of wheat decreased under organic farming while yields of soybean were not affected by the treatments. Based on our data we suggest that reduced plant water use observed under organically managed farming lead to the observed higher soil moisture in organically compared to conventionally managed farming systems in the DOK trial. These results suggest advantages of organic farming regarding agronomic water use as well as for the resistance of farming systems to current or future drought scenarios.

1. Introduction

Agricultural practices are often accompanied by a range of environmental costs including soil degradation, freshwater contamination, eutrophication, and biodiversity and habitat loss (McLaughlin and Mineau, 1995; Pimentel et al., 1995; Bennett et al., 2001; Pimentel, 2005; Gomiero et al., 2011). Organic agriculture has been suggested as a more sustainable alternative with lower environmental costs than conventional high-input agriculture (Dimitri and Greene, 2002; Vogt, 2007). Organic agriculture combines traditional farming methods such as natural pest management, rotating crops, and organic fertiliser application with modern technologies including biological control and reduced tillage (Cooper et al., 2016; Reganold and Wachter, 2016; Peigné et al., 2016). Today's share of organic to total farmland is 1% globally, 7% in the EU, and 14% in Switzerland (Eurostat, 2019; Willer and Lernoud, 2019).

Several long-term studies compared conventional and organic agricultural practices regarding yield and environmental impact (e.g. Drinkwater et al., 1998; Pimentel et al., 2005; Spargo et al., 2011; Forster et al., 2013; Cates et al., 2016). These studies revealed yield differences between organic and conventional agriculture that range from 5% to 35% less yield in organic agriculture, depending on the crop type and agroecological condition (Seufert et al., 2012). At the same time, there is ample scientific evidence that organic agriculture improves soil quality and soil fertility, conserves biodiversity, increases energy and production efficiency, and reduces environmental pollution

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compared to conventional agriculture (Mäder et al., 2000; Reganold et al., 2001; Mäder et al., 2002; Bengtsson et al., 2005; Hole et al., 2005; Fließbach et al., 2007; Forster et al., 2013; Wheeler et al., 2015; Reganold and Wachter, 2016; Di Prima et al., 2018).

To date, only a few studies have compared the impacts of organic versus conventional agriculture on the water relations of crops and/or entire cropping systems. This is surprising, given the importance of water for crop production and the fact that agriculture is the largest consumer of freshwater, leading industry and domestic use (WWAP, 2019). The previously shown impact of organic agriculture on soil properties implies that organic agriculture could also improve ecosystem water relations. Organically managed soils have, for example, a greater soil organic matter content (Liebig and Doran, 1999; Fließbach et al., 2007; Gattinger et al., 2012), which directly correlates with higher soil aggregate stability and reduced bulk density (Tisdall and Oades, 1982; Oades, 1984; Reganold et al., 1993). Both contribute to the water holding capacity of soils (Ohu et al., 1985; Rawls et al., 2003; Abdi et al., 2018). Some studies report higher resistance against surface runoff of organically as compared to conventionally managed soils because organic agriculture increases anectic ('vertical-burying') earthworm biomass and diversity which in turn results in a higher abundance of vertical earthworm tunnels and improved water infiltration (Edwards et al., 1990; Siegrist et al., 1998). In fact, Pimentel et al. (2005) as well as Kundel et al. (2020) reported higher ground-water recharge and soil moisture in organic compared to conventional farming approaches. Further indications for improved ecosystem water relations result from studies reporting higher crop yields in organic compared to conventional farming systems under drought conditions (Lotter et al., 2003; Pimentel et al., 2005). Despite these indications, studies directly assessing the plant and ecosystem water relations of crops in organically versus conventionally managed agroecosystems are scarce and just about starting to roll (Sun et al., 2021a, 2021b). Whether organic agriculture can indeed reduce the water demand and improve the water use efficiency of crop production still remains unclear.

In the work we present here, we assessed how conventional and organic farming systems affected the water relations of soils and crops in the 2017 and 2018 growing seasons. Our study was conducted in the DOK (bio-Dynamic, bio-Organic & 'Konventionell') system comparison trial, established as a collaboration of the Swiss Research Institute of Organic Agriculture (FiBL) and Agroscope in 1978 near Basel, Switzerland. The DOK trial is one of the world's oldest existing field trials comparing organic to conventional agriculture (Fließbach et al., 2007; Krause et al., 2020). We used the DOK trial to test (i) if soil moisture and soil surface evaporation are affected by conventional and organic farming, and (ii) if organically and conventionally grown plants differ in their root water uptake depth, stomatal conductance and leaf area. Based on these assessments, we (iii) made a rough evaluation of the total water use of the studied organic and conventional farming systems.

2. Materials and Methods

2.1. Study site and setup

This study was conducted in the DOK (bio-Dynamic, bio-Organic, C(K)onventional) trial in Therwil near Basel, Switzerland (47°50′25.69″ N, 7°53′93.28″ E, 306 m a.s.l.). In the DOK trial, organic and conventional farming systems have been compared since 1978 (Siegrist et al., 1998; Mäder et al., 2002; Fließbach et al., 2007; Krause et al., 2020). Mean annual temperature of the region for the years 2007–2017 is 10.9 °C with bimonthly means of 2.7 °C for Jan/Feb and 19.8 °C for July/Aug. Mean annual precipitation for the years 2007–2017 is 849.2 mm, 59% of which fall during the growing season from May to October (MeteoSwiss station Basel / Binningen). The soil is a Haplic Luvisol consisting of 70% silt, 16% clay and 14% sand (Mäder et al., 2002).

We investigated two crops during two growing seasons: winter wheat (*Triticum aestivum*, L.), cultivar *Wiwa* (seasons of 2017 and 2018) and soybean (*Glycine max*, L.), cultivar *Aveline* (season of 2017). For the 2017 season, wheat was sown on day of year (DOY) 288 in 2016 and harvested on DOY 199 in 2017. Soybean was sown on DOY 114 and harvested on DOY 265 in 2017. For the 2018 season, wheat was sown on DOY 292 in 2017 and harvested on DOY 194 in 2018. The winter wheat on which we additionally measured leaf area indices was of cultivar *Montalbano* and sown on DOY 299 of 2019.

For our assessment we focussed on the biodynamic and conventional mineral farming systems of the DOK trial. For the sake of simplicity, the biodynamic farming system is thereafter referred to as "organic" farming system or treatment. Both treatments were set up randomised with 4 plots of 100 m^2 (5 × 20 m) each per treatment and crop and followed a 7-year crop rotation (Mäder et al., 2002; Krause et al., 2020). The distance between cropping areas under the same treatment was 1.5 m and between different treatments at least 6 m. All measurements were performed inside the crop cultures with a distance of at least 50 cm to the adjacent grasslands to avoid across-treatment contamination. organic and conventional farming systems differed mainly in their fertilization and plant protection strategy. Organic systems were fertilized with composted farm yard manure and slurry, while conventional systems were fertilized with mineral fertilizer exclusively. Unlike in the organic treatment, conventionally grown winter wheat was treated with the growth regulator chlormequat chloride (CCC). No growth regulators were applied on soybean under both treatments. The organic treatment further received biodynamic preparations which were applied to soils, plants and compost. Tillage, crop rotation and cultivars planted are identical in the two treatments. More details on cultivation for each crop species during the seasons 2017 and 2018 can be found in Table S1 and a detailed description of the trial setup can be found in Besson and Niggli (1991) and Krause et al. (2020).

2.2. Soil hydrological properties

For winter wheat 2017 and soybean (until DOY 173 in 2017), the volumetric moisture content at 10 cm soil depth was determined manually with a handheld device (ML2 Moisture Meter, Delta-T Devices, Cambridge, UK) with one measurement per plot (and four plots per treatment and crop species, n = 4). Starting on DOY 177 of 2017, measurements of volumetric moisture content were performed manually with the PR2 SDI-12 Soil Moisture Profile Probe (Delta-T Devices, Cambridge, UK) which allowed simultaneous measurements at 10 cm, 20 cm, 30 cm, 40 cm, 60 cm, and 100 cm soil depth in pre-installed PVC tubes. We installed one tube for Soil Moisture Profile Probe measurements per plot and four per treatment and crop species (n = 4). The devices were calibrated using the installed calibration setup of the HH2 Moisture Meter read-out unit (Delta-T Devices, Cambridge, UK). In 2017 the measurements were repeated every ~14 days between the beginning of March and beginning of July for winter wheat, and between middle of April and end of August for soybean, respectively (Fig. 1). Between March and July of 2018, measurements were repeated weekly for wheat.

To assess if potential treatment effects on soil moisture are the result of differences in the water balance (i.e. input vs. output) or the result of soil physico-chemical properties, we determined soil water retention capacities in the two treatments. For this purpose, in each treatment one soil sample (250 cm^2, 5 cm core height) per plot (n = 4) was collected on DOY 355 in 2017 at 15 cm soil depth. These samples were analyzed with a HYPROP device (UMS GmbH, Munich, Germany), which is based on the evaporation method proposed by Schindler (1980). After drying the soil for 24 h at 105 °C and weighing it, the absolute soil moisture contents were calculated from initial volumetric soil moisture contents and dry soil weight using the HYPROP-FIT software v. 3.3.0 (UMS GmbH, Munich, Germany). The measured pF values were interpolated using loess interpolation with R v. 3.4.1 (R Core Team, 2017) and pF values were calculated for 19 absolute moisture contents to subsequently test treatment effects using Student's t-test.

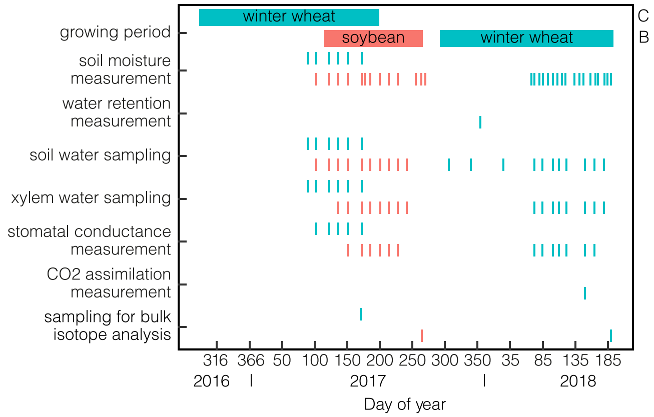

Fig. 1. Overview of sampling events throughout the growing periods of winter wheat and soybean between October 2016 and July 2018. Wheat and soybean were grown on the respective cropping area indicated by C and B (S1). Each vertical coloured line represents one single sampling event (n = 4). Here, growing periods are defined as the periods between sowing and harvest. A detailed list of measures and sampling dates can be found in Tab. S1).

2.3. *Soil and plant water stable isotope sampling, extraction, and analysis*

We used the oxygen and hydrogen stable isotope composition ($\delta^{18}O$ and $\delta^{2}H$, respectively) of precipitation and soil water to obtain information on critical soil hydrological processes (Stumpp and Maloszewski, 2010; Mueller et al., 2014). This method utilized deviations in the slope of the relationship between $\delta^{18}O$ and $\delta^{2}H$ values in soil water from the slope of the relationship between $\delta^{18}O$ and $\delta^{2}H$ values of local precipitation to characterize evaporative water loss from the soil (Zimmermann et al., 1967; Wenninger et al., 2010).

For the determination of $\delta^{18}O$ and $\delta^{2}H$ values in precipitation, we installed three 'ball-in-funnel' precipitation samplers with inlet, built after (Prechsl et al., 2014), at the trial site. Precipitation was collected from the samplers every 7–14 days during the growing season. The water samples were filtered using 0.45 μm polyethersulfone syringe filters (BGB Analytik USA LLC, Alexandria, VA, USA), transferred into 1.5 mL air-tight glass vials (BGB Analytik USA LLC, Alexandria, VA, USA) and analyzed in subsequent weeks (see below).

For the determination of the soil water $\delta^{18}O$ and $\delta^{2}H$ values, we collected soil water samples throughout the experiment. Soil sampling was repeated approximately every 14 days between end of March and the beginning of July for wheat, and between middle of April and end of August for soybean, respectively (Fig. 1). Soil samples were also collected three times in the off season between DOY 306 in 2017 and DOY 25 in 2018. For the collection of samples, we took one soil core per plot (n = 4 per treatment) with a 28 mm-diameter soil corer ('Pyrkhauer', Goecke GmbH & Co. KG, Schwelm, Germany). From the core we collected soil samples at − 2.5 cm, − 10 cm, − 20 cm, − 30 cm, − 50 cm and − 70 cm soil depth (± 2.5 cm). All samples were stored in 12 mL air-tight glass exetainers (Labco, Lampeter, U.K.) at − 18 °C until the water was extracted (for extraction procedure see below).

On the exact same days of soil water sampling, we also collected plant samples for the determination of xylem water $\delta^{18}O$ values. Assuming that plant water uptake does not affect the stable isotope composition of water (Chen et al., 2020), the comparison of $\delta^{18}O$ values of xylem water to $\delta^{18}O$ values of soil water can be used to determine the plant's water uptake depth (White et al., 1985; Ehleringer and Dawson, 1992; Meinzer et al., 1999). To obtain xylem water, we collected the root crowns of three plants per sample as suggested by Barnard et al. (2006). Samples were collected in four plots per treatment and crop species (n = 4). We used a loess interpolation of the $\delta^{18}O$ soil water values along the soil profile and subsequently inserted the xylem isotope values into the model to determine the uptake depth of xylem water sampled.

For the extraction of water from soil and plant samples we used the cryogenic water extraction method as described in Newberry et al. (2017b). Recent studies have suggested isotope artefacts associated with the cryogenic extraction of water from plant and soil samples (Zhao et al., 2016; Orlowski et al., 2016, 2018; Newberry et al., 2017a; Barbeta et al., 2020; Freyberg et al., 2020). These potential artefacts are carefully considered in the interpretation of $\delta^{18}O$ and $\delta^{2}H$ data in this study.

The $\delta^{18}O$ and $\delta^{2}H$ values of precipitation, soil and xylem water samples was determined with a high-temperature conversion/elemental analyzer (TC/EA) coupled to a DELTA V Plus continuous-flow isotope ratio mass spectrometer (IRMS) via a ConFlo IV interface (Thermo Fisher Scientific, Bremen, Germany). The samples were pyrolyzed at 1400 °C and oxygen was converted into CO using the carbon reduction method after Gehre et al. (2004). Analytical sequences and post-run corrections were performed using calibrated laboratory standards according to Werner and Brand (2001). The $\delta^{18}O$ and $\delta^{2}H$ values were calculated relative to the Vienna Standard Mean Ocean Water (VSMOW) and expressed in ‰. The precision of the lab's quality control standard water was ± 0.09‰ and ± 0.23‰ for $\delta^{18}O$ and $\delta^{2}H$, respectively.

2.4. *Crop physiological properties and yield*

To assess effects of different agricultural farming systems on plant water relations, we measured midday stomatal conductance (g_s). g_s was measured in all plots of both crops and farming systems on the abaxial side of one (year 2017) and three (year 2018) sun-exposed leaves in ~14-day intervals (Fig. 1) using a SC-1 Leaf Porometer (METER Group, Inc., Pullman, WA, USA). We also measured $\delta^{18}O$ values of dried wheat leaf and soy bean material as an independent and temporally integrative proxy for treatment effects on g_s (Barbour, 2007; Grams et al., 2007; Cernusak et al., 2016). For winter wheat, we collected the youngest flag leaf of five individuals per plot on DOY 171 in 2017 and DOY 190 in 2018. After collection, leaves were dried for 24 h at 60 °C. For soybean, we collected beans in a 22.5 m^2 (15 ×1.5 m) area of the central row of each plot on DOY 265 in 2017. After collection, the beans were dried at room temperature (20 °C) for 72 h. The winter wheat leaves were finely ground with a horizontal ball-mill (MM 400, Retsch, Haan, Germany) in 2 mL PP Eppendorf tubes (SARSTEDT AG & Co. KG, Nümbrecht, Germany) using 5 mm glass beads (Assistent®, Sondheim/Rhön, Germany). The soybean beans were ground using metal beads (Schieritz & Hauenstein AG, Arlesheim, Switzerland).

To measure bulk $\delta^{18}O$ values, 0.2–0.5 mg of the dried sample was transferred into 6 × 4 mm silver capsules (OEA Labs Ltd, Cornwall, UK). Subsequently, the samples were introduced into a Flash IRMS (Thermo Fisher Scientific, Bremen, Germany) operated in TC/EA mode using a Costech Zero Blank Autosampler (Costech International, Milan, Italy). The $\delta^{18}O$ values were normalized relative to the Vienna Standard Mean Ocean Water (VSMOW) with an analytical precision of ± 0.09‰. All isotopic measurements were conducted in the Stable Isotope Ecology Laboratory at the Department of Environmental Sciences of the University of Basel, Switzerland.

In all winter wheat plots of both farming systems, leaf area indices (LAI) were assessed in triplicates above and below the canopy on DOY

174 in 2020 using the PAR/LAI ceptometer AccuPAR LP-80 (Decagon Devices). Per plot, the sub-replicated measurements were then averaged and LAIs were calculated following the equation of Monsi and Saeki (1953):

$$I = I_0 e^{-k \quad LAI}$$

Where I and I_0 are the light intensities under and above the canopy, respectively, and k is the light extinction coefficient here chosen as 0.42 (Calderini et al., 1997; Evers et al., 2009).

To link plant water relations to agricultural production, we assessed grain and straw dry matter yield of soybean on DOY 265 in 2017 and of winter wheat on DOY 199 and DOY 193 in 2017 and 2018, respectively. Wheat and soybean were harvested with a plot combine (Wintersteiger AG, Bad Sassendorf, Germany) and dried with cold air (20 °C) for approximately 72 h before calculating the mean treatment yield per hectar (ha).

2.5. Statistical analyses

Statistical analyses were done with R v. 3.4.1 (R Core Team, 2017), using its packages ggplot2 (Wickham, 2016) for graphical visualisation, agricolae (de Mendiburu, 2017) for post hoc tests and nlme (Pinheiro et al., 2018) for linear mixed effect modelling. To account for repeated measurements on the plot level, soil moisture, water uptake depth and stomatal conductance data were analyzed using linear mixed-effect models with treatment and time defined as fixed, and plot specified as random effect, respectively (Pinheiro and Bates, 2011). Homogeneity and normal distribution of residuals were confirmed visually and, if needed, the tested variables were log-transformed prior to analysis.

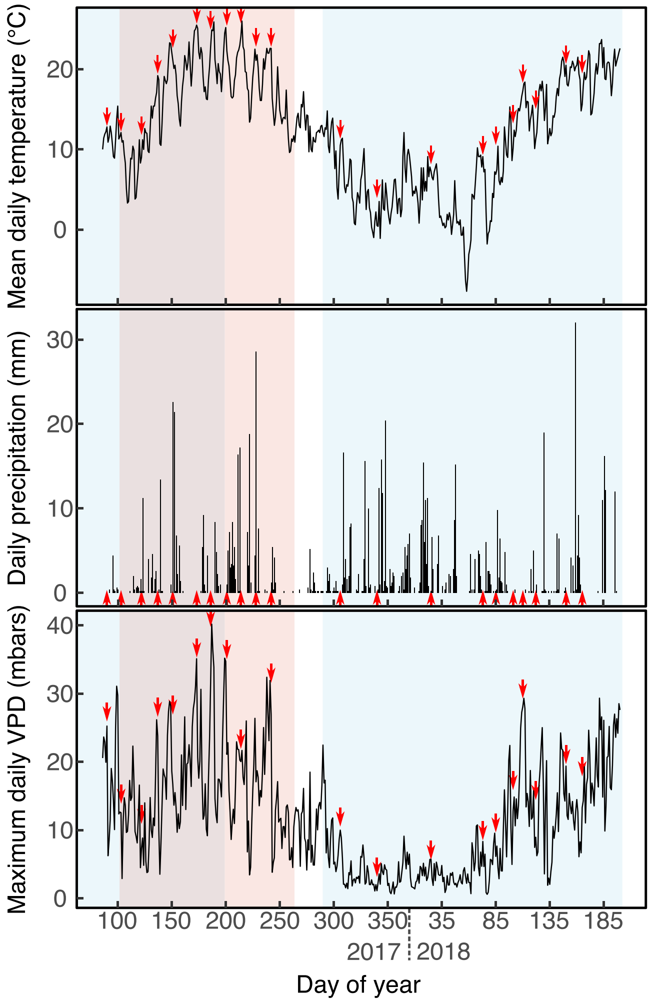

Fig. 2. Temperature, precipitation and vapour pressure deficit (VPD) measured by the weather station at the DOK trial site. Temperature data of the periods DOY 295 (2017) – 52 (2018) and DOY 66 – 78 (2018) were replaced with data from the MeteoSwiss weather station Binnigen (BL) in the near vicinity. The growing seasons of wheat and soybean are indicated by blue and red boxes, respectively. The sampling dates are marked with red arrows.

3. Results

3.1. Weather conditions

Mean annual precipitation at the trial site was 582 mm and 614 mm in 2017 and 2018, respectively (Fig. 2). The mean growing season precipitation (May – Oct) was 22% lower in 2017 and 30% lower in 2018 compared to long-term trends (2007–2017) obtained from a nearby weather station (MeteoSwiss station Basel / Binningen). Mean annual temperature at the trial site was 10.8 °C for 2017 and 11.8 °C for 2018, with bimonthly means of 1.1 °C and 3.4 °C for Jan/Feb and 20.2 °C and 21.3 °C for July/Aug, respectively. The temperatures at the

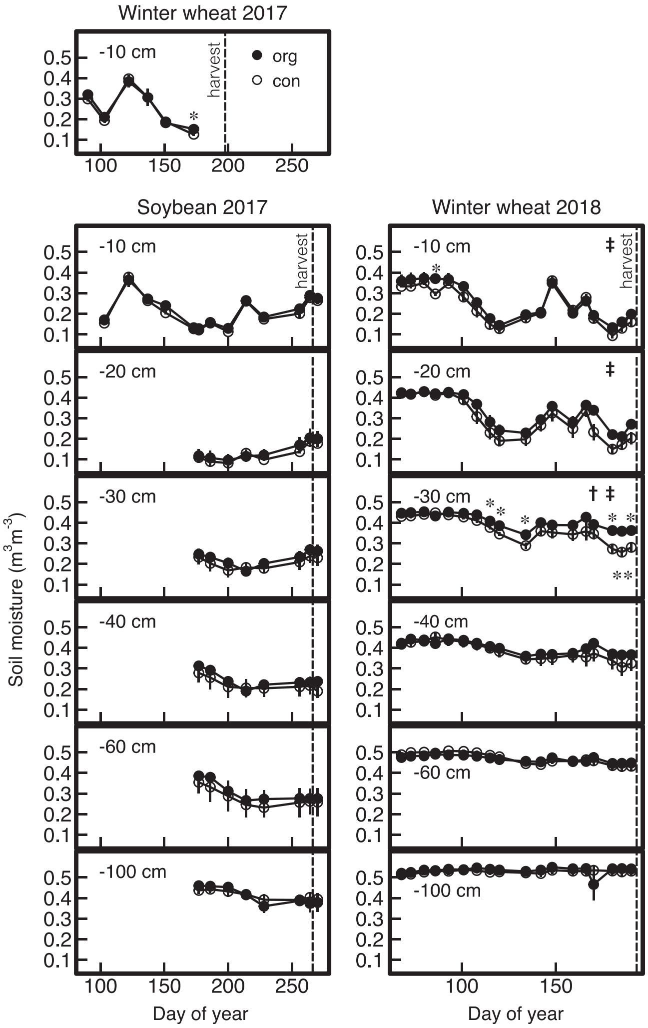

Fig. 3. Volumetric soil moisture content (mean ± SE, n = 4) of the organically (org) and conventionally (con) managed winter wheat and soybean plots in 2017 and 2018. Significant treatment differences after time-series analysis are indicated by † (with $p < 0.05$, Table 4) and significant treatment-time interactions by ‡ (with $p < 0.05$ for −10 and −20 cm, and $p < 0.001$ for −30 cm). Statistically significant treatment differences at specific sampling dates are marked with asterisks (with * $p < 0.05$ and **$p < 0.01$).

trial site are generally 1 K lower than the temperatures measured at the MeteoSwiss weather station Basel-Binningen, whose 10 year average annual temperature is 10.9 °C and long-term bimonthly means are 2.7 °C for Jan/Feb and 19.8 °C for July/Aug.

3.2. *Soil hydrological properties*

Volumetric soil moisture contents measured in the season 2017 decreased after DOY 122 and increased again with heavy precipitation events after DOY 200 in 2017 (Fig. 3). Soil moisture generally increased with soil depth, except for the soybean plots at − 20 cm which showed the lowest values of the 2017 season. We also found a slight but consistent tendency for higher moisture contents in soils with soybean under the organic treatment at 20–60 cm soil depth compared to soils with soybean under the conventional treatment in 2017. However, this tendency was statistically not significant. In winter wheat grown in 2017 we did not see any differences in soil moisture at 10 cm soil depth. We found, however, consistently higher soil moisture in soils with winter wheat under organic compared to conventional farming treatment in 2018 at 10 cm, 20 cm and 30 cm and a similar tendency at 40 cm soil depth towards the end of the growing period. The treatment effects on soil moisture were significant in 2018 at 30 cm soil depth ($p < 0.05$ after time-series analysis, Table 1). In the same season, we further found significantly different treatment-time interactions at 10, 20 ($p < 0.05$) and 30 cm soil depth ($p < 0.001$) where the seasonal amplitude of soil moisture in the conventional treatments was greater compared to the amplitude of soil moisture in the organic treatments in 2018.

pF values increased linearly with decreasing soil moisture and increased slightly slower after the soil reached 35% moisture content (Fig. 4). Organic and conventional soil matrix potentials at specific soil moisture contents were not significantly different from each other using Student’s t-test of pF values at separate soil moisture levels (Table 2).

3.3. *Ecohydrological properties derived from soil and plant water stable isotope analysis*

The $\delta^{18}O$ and $\delta^{2}H$ values of precipitation collected at the trial site fitted well into the seasonal course of the precipitation values collected at the Basel GNIP station when plotted in dual isotope space (Fig. 5a). However, the slopes of the local DOK meteoric water line and the GNIP meteoric water line differed significantly at $p < 0.001$ (Fig. 5a, Table 3). This can be explained by the smaller range of DOK compared to GNIP $\delta^{18}O$ and $\delta^{2}H$ values, due to the fact that winter precipitation was not collected at the DOK for this study.

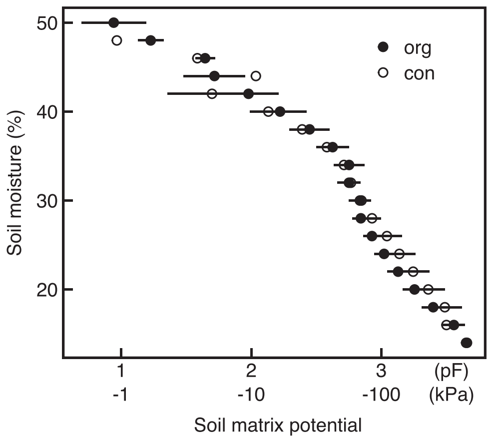

Fig. 4. Water retention curves (mean ± SE, n = 4) of organic (org) and conventional (con) soil. We found no significant differences between the treatments (Table 2).

The soil water $\delta^{18}O$ and $\delta^{2}H$ values followed a similar seasonal pattern as precipitation $\delta^{18}O$ and $\delta^{2}H$ values collected at the DOK (Fig. 5b). The seasonal amplitude decreased, however, with increasing soil depth (Fig. 5c). When plotted in dual isotope space, the slope for all soil water $\delta^{18}O$ and $\delta^{2}H$ values (5.7) was significantly less steep than that of both local meteoric water lines (LMWLs) obtained from the DOK and GNIP precipitation values ($p < 0.001$) (Fig. 5b). Separating soil water dual isotope lines by soil depths revealed increasing slopes from 2.5 to 20 cm soil depth (Fig. 5c). Regardless of soil depth, slopes and intercepts of soil water lines did not differ significantly between the

Table 1
ANOVA of linear mixed-effect modelled time series analyses of soil moisture (Fig. 3). Each depth has been tested separately. Formula in R: lme(moisture ~ treatment*time, random = ~1| plot, method = "REML", data). a) was obtained by counting the days on which differences in soil moisture between the organic and conventional treatment were significant ($p < 0.05$) after student’s t-test.

Species	Depth (cm)	Coefficient	numDF	denDF	F-value	*p*-value	Nr. of days significant[a])
Soybean 2017	-10	treatment	1.00	6.00	1.11	0.332	0
		treatment:d	12.00	72.00	0.26	0.993	
	-20	treatment	1.00	7.00	0.02	0.896	0
		treatment:d	7.00	41.00	0.73	0.646	
	-30	treatment	1.00	7.00	0.10	0.766	0
		treatment:d	7.00	41.00	1.16	0.347	
	-40	treatment	1.00	7.00	0.11	0.746	0
		treatment:d	7.00	41.00	1.23	0.308	
	-60	treatment	1.00	7.00	0.10	0.766	0
		treatment:d	7.00	41.00	0.21	0.981	
	-100	treatment	1.00	7.00	0.03	0.872	0
		treatment:d	7.00	41.00	0.75	0.631	
Winter wheat 2017	-10	treatment	1.00	6.00	0.28	0.618	1
		treatment:d	5.00	30.00	0.50	0.775	
Winter wheat 2018	-10	treatment	1.00	6.00	1.07	0.340	1
		treatment:d	17.00	102.00	1.83	**0.034**	
	-20	treatment	1.00	6.00	1.61	0.251	0
		treatment:d	17.00	102.00	1.81	**0.036**	
	-30	treatment	1.00	6.00	6.39	**0.045**	6
		treatment:d	17.00	102.00	3.58	**< 0.001**	
	-40	treatment	1.00	6.00	0.37	0.565	0
		treatment:d	17.00	102.00	1.05	0.411	
	-60	treatment	1.00	6.00	0.03	0.872	0
		treatment:d	17.00	102.00	1.43	0.139	
	-100	treatment	1.00	6.00	0.10	0.763	0
		treatment:d	17.00	102.00	0.87	0.615	

Table 2
List of number of observations of pF values at specific volumetric soil moisture contents with student's t-tests for n ≥ 3.

Soil moisture (%)	Coefficient	Estimate	Std. error	t-value	*p*-value	R^2	Nr. of obs. organic	Nr. of obs. conventional
14	treatment						1	1
16	treatment						2	1
18	treatment						2	2
20	treatment						2	2
22	treatment						2	2
24	treatment						2	2
26	treatment						2	2
28	treatment						2	3
30	treatment	0.01	0.11	0.12	0.914	0.91	3	3
32	treatment	0.02	0.11	0.13	0.900	-0.24	3	3
34	treatment	-0.04	0.13	-0.29	0.780	-0.15	4	4
36	treatment	-0.04	0.14	-0.32	0.763	-0.15	4	4
38	treatment	-0.06	0.18	-0.32	0.761	-0.15	4	4
40	treatment	-0.09	0.25	-0.36	0.729	-0.14	4	4
42	treatment	-0.28	0.39	-0.71	0.508	-0.09	4	3
44	treatment						4	1
46	treatment						4	1
48	treatment						3	1
50	treatment						2	0

organic and conventional treatments (Table 3).

Xylem water $\delta^{18}O$ values of both crop species and years ranged from − 10.4‰ to − 0.7‰. Mean root water uptake depth (RWU) estimated from $\delta^{18}O$ values of winter wheat in 2017 stayed more or less constant throughout both seasons with the exception of DOY 173, where RWU dropped rapidly from − 7 to − 28 cm (Fig. 6). The RWU of soybean dropped more or less consistently throughout the growing season until it rose again after day 200 in 2017. RWU of winter wheat showed no clear seasonal trend in 2018. We observed no significant treatment effects on RWU. Only soybean showed RWU from deeper soil layers in the organic compared to the conventional treatment on two sampling days in 2017. These effects were, however, not significant.

3.4. *Crop physiological properties and yield*

Mean stomatal conductance (g_s) of winter wheat was significantly lower compared to soybean ($p < 0.001$, Fig. 7a). Winter wheat measured in 2017 and 2018 showed significantly lower g_s in the organic compared to the conventional treatment ($p < 0.05$, Table 5). Soybean in 2017 showed a similar tendency of lower g_s on 4 of 6 sampling days in the organic compared to the conventional treatment. These effects were, however, not statistically significant, neither were treatment-time interactions of both species in both years.

We found that bulk $\delta^{18}O$ values of both crop species wheat and soybean showed no statistically significant difference (Fig. 7b, Table 6). However, there was a consistent tendency for more positive values in the organic compared to the conventional treatment.

Leaf area index (LAI) measured in 2020 on winter wheat was significantly lower in organic compared to the conventional treatment (Fig. 8, $p < 0.05$, Table 6).

Straw yields of winter wheat did not differ between the organic and conventional treatment in 2017 but were significantly lower in the organic compared to the conventional treatment in 2018 (Fig. 9, Table 6). Grain yield of winter wheat was significantly higher in the conventional treatment in both years of sampling. Straw and grain yield of soybean was almost identical in both farming systems and did not differ significantly.

4. Discussion

The goal of this study was to assess how organic and conventional farming systems affect the water relations of soils and crops. In particular, we tested if organic and conventional farming systems lead to marked differences in soil moisture, soil evaporation, as well as root water uptake depth and the stomatal conductance of crops. Our results suggest no differences with regard to soil water evaporation but higher soil moisture in the rooting zone of organically compared to conventionally managed systems. The differences were statistically significant for wheat but not for soybean. Soil water retention curves suggest that soil physical properties do not explain the observed differences in soil moisture between the two systems at the trial site. Also, no differences in root water uptake depth between plants grown in organically or conventional farming systems was detected. We found, however, that organically grown wheat exhibited a generally lower stomatal conductance (g_s) compared to conventionally grown wheat. Soybean showed similar tendencies but treatment effects on g_s and soil moisture were smaller. In addition, we found that winter wheat (but not soybean) had lower dry matter yield and leaf area in organic farming systems compared to conventional farming systems. In summary, our study suggests that lower stomatal conductance and smaller leaf area under organic compared to conventional farming can reduce water use and resulted in higher soil moisture in organically compared to conventionally managed wheat at the DOK trial site.

4.1. *Soil hydrological properties*

Our study revealed trends of higher volumetric soil moisture in the organic compared to the conventional treatment (Fig. 3, Table 1). Specifically, soil moisture under wheat was higher in the organic compared to the conventional treatment at 10–30 cm in 2018 and a similar tendency was observable for soybean in 2017. Previous studies found higher water holding capacities under organic farming (Siegrist et al., 1998; Liebig and Doran, 1999; Wells et al., 2000; Lotter et al., 2003). These studies suggest that organic carbon (org C) and higher aggregate stability are responsible for these patterns. Previous analyses of soil

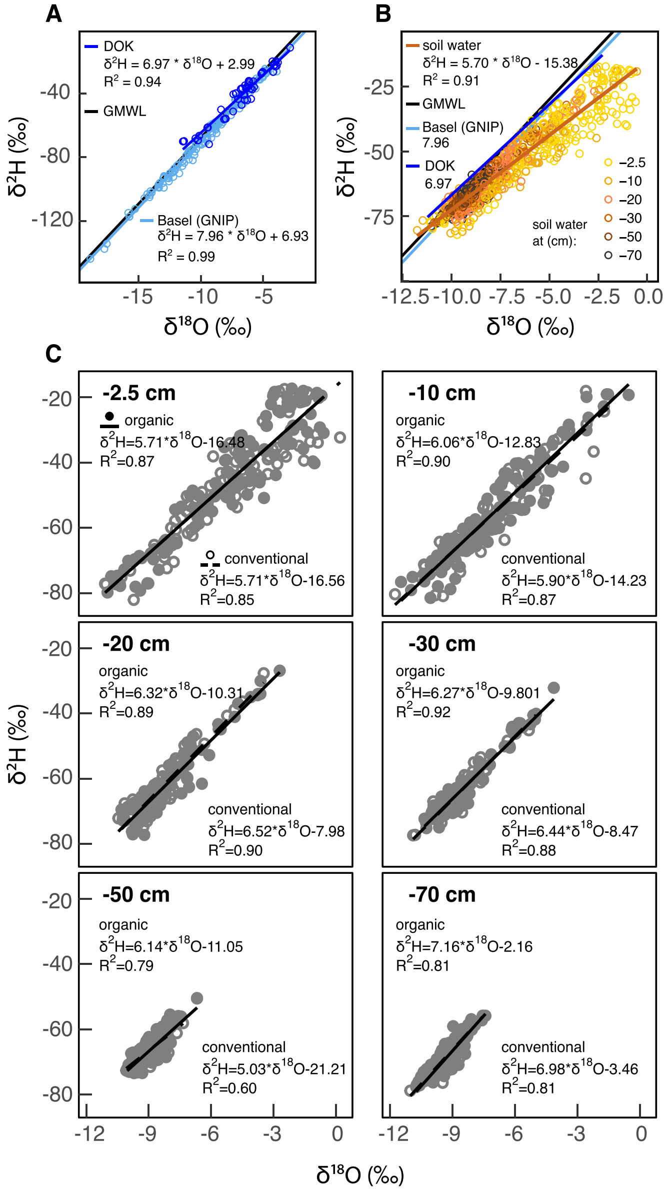

Fig. 5. Water stable δ^2H- and δ^{18}O-values in the dual isotope space. A: Water stable isotope values of precipitation collected at the Basel GNIP station between 2004 and 2016, and at the DOK trial in Therwil between 2017 and 2018. All linear regressions are highly significant with $p < 0.001$ (Table 3). B: Soil water stable isotope values of both treatments organic and conventional and both crops winter wheat and soybean of the seasons 2017 and 2018, compared to the precipitation lines. All linear regressions are highly significant with $p < 0.001$ (Table 3). C: Comparison of soil water stable isotope values between the organic (filled dots & solid line) and conventional (empty dots & dashed line) treatments at different soil depths of both crop species, wheat and soybean, in 2017 and 2018. There are no significant differences in the slopes and intercepts between the organic and conventional treatments (Table 3).

properties at the DOK trial have reported higher contents of org C and higher aggregate stability in organic compared to conventional systems (Mäder et al., 2002; Fliessbach et al., 2007). The observed trend in soil moisture between the two treatments in our study could thus be the result of a larger storage capacity in organic compared to conventional soils driven by the previously reported differences in physicochemical properties. Importantly, however, differences in soil moisture between the two treatments were most expressed when soils became dry (Fig. 3). This suggests that water holding capacity is not the driver of the observed patterns as differences in water holding capacity should become most evident in wet soils. Interestingly, Kundel et al. (2020) found similar soil moisture patterns at the same trial for winter wheat in 2017, but their effects were strongest under ample soil water conditions.

Alternatively, the observed trends in volumetric soil moisture between the two treatments could be the result of differences in water retention capacities resulting in a less efficient water extraction from the organic compared to the conventional soils. This would mean that the higher volumetric soil moisture observed in the organic compared to the conventional trials, in particular in drying soils, are merely the result of residual water that is not available to the plants. The water retention capacity of a soil is determined by soil physical properties such as soil texture but also org C content (Rawls et al., 2003; Saxton and Rawls, 2006). Given that org C content was higher in organic compared to conventional soils (Fließbach et al., 2007; Kundel et al., 2020), we determined soil water retention capacities in the two treatments with pF curves. We, however, did not find any difference in the pF-curves between the organic and the conventional treatments (Fig. 4, Table 2). However, technical limitations only enabled measurements of pF values at volumetric moisture contents greater than 13.7 vol%. But looking at the soil moisture data of wheat in 2018, we already observe treatment differences in moisture contents greater than 40% at − 10 to − 30 cm soil depth. Also, the amount of measured soil moisture contents below 13.7 vol% is relatively small (on 1 and 2 sampling days in the organic and conventional treatment, respectively) and only observed at − 10 cm. In soybean, moisture values below 13.7 vol% were measured mainly at − 20 cm without resulting in significant treatment differences. As a consequence, we conclude that the observed trends in soil moisture patterns between the two treatments are unlikely a result of differences in soil matrix potentials.

Comparing the relationship between δ^{18}O and δ^2H values of soil water with those of precipitation can reveal information on soil hydrological processes such as infiltration, residence time or evaporation (Brinkmann et al., 2018; Penna et al., 2018; Sprenger et al., 2019; Dawson et al., 2020; Freyberg et al., 2020). Precipitation stable isotope values of the Basel GNIP station as well as precipitation samples collected at the DOK trial site, i.e. the local meteoric water line (LMWL), plotted close to the GMWL (Fig. 5a). In contrast, when soil water δ^{18}O and δ^2H values were plotted in a dual isotope space we observed that the slope of soil water lines was significantly less steep than that of the LMWL (Fig. 5b). Given that evaporation fractionates oxygen and hydrogen isotopes in water differently, the shallow slopes of the soil water lines suggest evaporative water loss from the soil to the atmosphere (Clark and Fritz, 1997). When dividing the soil water line into single soil water lines for individual soil depths, we observed less steep slopes in shallower compared to deeper soil layers (Fig. 5c). This suggests, that evaporative water loss is more pronounced in shallow compared to deep soil layers (Wythers et al., 1999). Most importantly, the slopes of these depth-specific evaporation lines did not differ between the organic and conventional treatments (Fig. 5c, Table 2), which suggests that evaporative water loss does not differ between the organic and the conventional treatments. In turn, this implies that differences in evaporative water loss cannot explain the observed trend in soil moisture between the two treatments. Amooh and Bonsu (2015) suggested a negative correlation between soil organic matter and evaporative water loss. Despite higher soil organic matter contents and higher weed coverage in organic compared to conventional systems (Fließbach et al., 2007; Kundel et al., 2020), the different farming systems did not affect evaporative water loss in our case. However, soil coverage or tillage did not differ between the treatments investigated in this study. Such measures are often part of sustainable farming approaches and have been shown to considerably affect soil water evaporation (Lin, 2010; Abdullah, 2014; Li et al., 2020).

We used the cryogenic extraction technique to obtain water from soil samples for stable isotope analysis following the procedure described in Newberry et al. (2017b). Several previous studies have revealed that the cryogenic extraction method can introduce isotope artefacts to the

Table 3

ANCOVA of precipitation water slopes in the dual isotope space between different precipitation sources (GNIP station and DOK values) and ANCOVA of soil water slopes in the dual isotope space between the treatments organic and conventional. For soil water values, each soil depth was tested separately and tested values include both species, wheat and soybean and both measured years, 2017 and 2018. Values obtained from the coefficients 'source' and 'treatment' indicate differences between intercepts, values obtained from the interaction 'source:$\delta^{18}O$' or 'treatment:$\delta^{18}O$' indicate differences between slopes.

Source	Soil depth (cm)	Coefficient	Df	Sum Sq	Mean Sq	F-value	*p*-value
precipitation GNIP – precipitation DOK		source	1	5366	5366	547.76	**< 0.001**
		source:$\delta^{18}O$	1	644	644	65.72	**< 0.001**
soil water – precipitation DOK		source	1	5058	5058	325.88	**< 0.001**
		source:$\delta^{18}O$	1	381	381	24.52	**< 0.001**
organic – conventional	-2.5	treatment	1	0	0	0.00	0.962
		treatment:$\delta^{18}O$	1	0	0	0.00	0.982
	-10	treatment	1	3	3	0.14	0.710
		treatment:$\delta^{18}O$	1	6	6	0.28	0.597
	-20	treatment	1	21	21	2.25	0.135
		treatment:$\delta^{18}O$	1	4	4	0.45	0.503
	-30	treatment	1	1	1	0.19	0.660
		treatment:$\delta^{18}O$	1	2	2	0.33	0.569
	-50	treatment	1	10	10	1.93	0.166
		treatment:$\delta^{18}O$	1	20	20	3.87	0.051
	-70	treatment	1	7	7	1.36	0.245
		treatment:$\delta^{18}O$	1	1	1	0.15	0.702

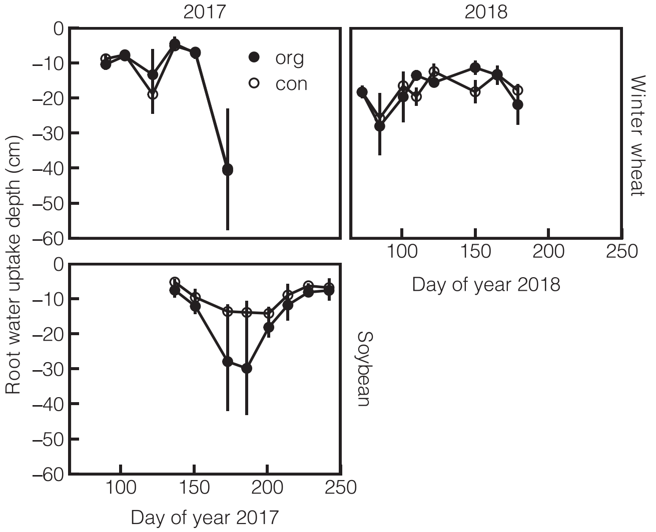

Fig. 6. Estimated root water uptake (RWU) depth (mean ± SE, n = 4) of wheat and soybean in the two treatments organic (org) and conventional (con) in 2017 and 2018. Values of RWU depth were derived by comparing $\delta^{18}O$ values in plant xylem water to those in soil water at different depths. Differences between the two treatments were not statistically significant (Table 4).

extracted soil water and that factors such as soil texture can influence the magnitude of these artefacts (Orlowski et al., 2016, 2018; Zhao et al., 2016; Newberry et al., 2017a; Barbeta et al., 2020; Freyberg et al., 2020). As such, soil water isotope values obtained with the cryogenic extraction methods need to be interpreted with the consideration of these methodological artefacts. For the data that we present here, it is unlikely that potential artefacts influence the main findings of our study. This is, because it was the main objective of our study to assess differences in soil hydrology between the organic and the conventional treatment. Potential artefacts associated with the cryogenic extraction of soil water are thus identical for samples from both treatments and although these artefacts might introduce errors in absolute $\delta^{18}O$ and $\delta^{2}H$ values, they do not influence the comparison of the two treatments.

4.2. Plant water relations

Given that previous studies have shown higher bulk density and root penetration resistance in conventional compared to organic farming systems (Reganold et al., 1993; Mäder et al., 2002; Chaves et al., 2003), we expected root water uptake (RWU) depths from deeper soil layers of plants in the organic treatment compared to the conventional treatment. Surprisingly, our results did not confirm our expectations. We detected no significant differences in RWU depth between the two treatments in both years and in both species (Fig. 6, Table 4). This is in line with recent findings of Sun et al. (2021b) showing no effect of organic and conventional cropping systems on water uptake patterns of pea and barley. However, soybean plants in the organic treatment showed slightly deeper RWU depths than plants in the conventional treatment, especially when soil moisture was progressively decreasing between DOY 173 and 214 in 2017. This suggests that soybean plants in the organic treatments have access to deeper soil water and thus a larger soil water pool than soybean plants grown in the conventional treatment. Easier root growth in organic soils which have a lower bulk density or a larger water uptake horizon by greater arbuscular mycorrhizal colonization under the organic regime is a possible explanation for the observed patterns in soybean (Reganold et al., 1993; Al-Karaki, 1998; Mäder et al., 2000; Mäder et al., 2002). However, it is possible that RWU patterns similar to the ones observed on soybean were not detected on winter wheat since wheat plants in the conventional treatment were treated with the growth regulator chlormequat chloride (CCC). CCC has been shown to increase the rooting depth of wheat (De et al., 1982; Tang et al., 2005). It could therefore be possible that effects of organic farming on RWU depth could have been countervailed by the application of CCC in the conventional treatment. Also, the differences in root morphology between wheat and soybean having an adventitious and a tap root system, respectively, may be a possible reason for the contrasting patterns observed between the two crops.

We found that stomatal conductance of wheat was significantly lower under the organic compared to the conventional treatment and that there was a similar tendency for soybean (Fig. 7a, Table 5). This suggests lower per leaf area transpiration rates of wheat growing in the organic compared to the conventional treatment. Given that water retention did not differ between the treatments and soil moisture under wheat was generally higher in the organic treatment at 10–30 cm soil depth, the observed differences in g_s of wheat are most likely not a response to moisture availability. g_s as well as photosynthetic assimilation were shown to be positively related to N availability (Radin et al., 1982; Broadley et al., 2001; Fang et al., 2018). However, we observed mixed results for plant N concentrations and slightly higher assimilation rates in organically grown wheat in 2018 (Fig. S2&3, Tab. S2&3). Hence, N availability can also not explain g_s patterns observed in this study. It is possible that plant intrinsic factors or pathogen-induced

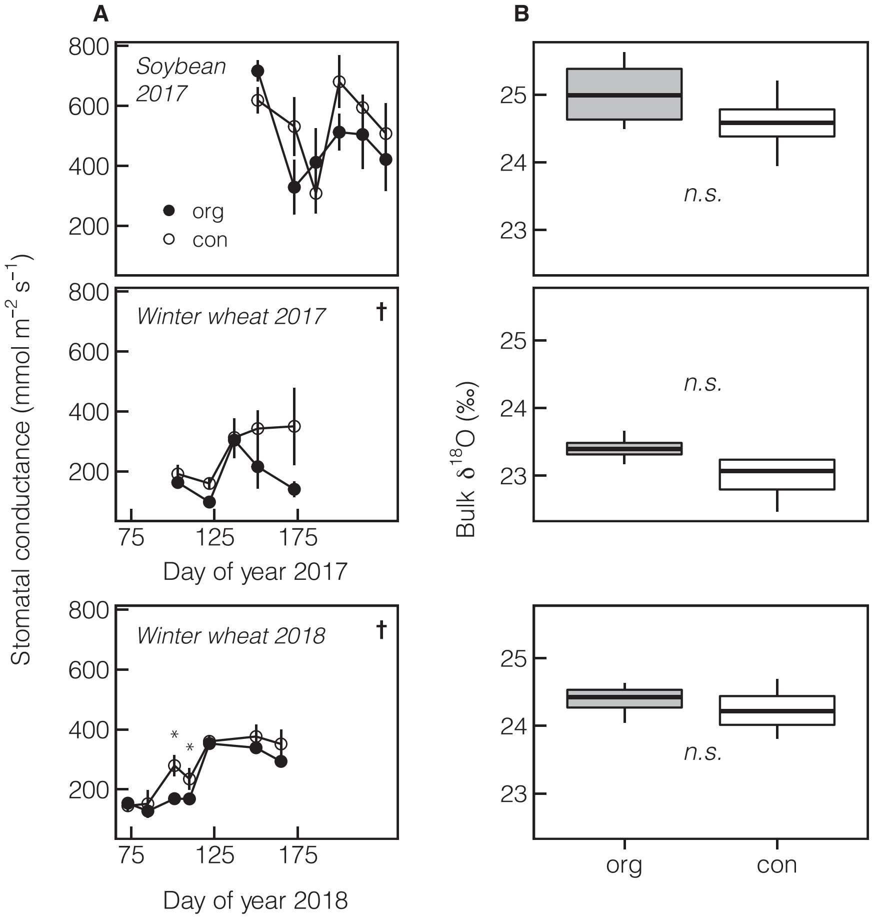

Fig. 7. Differences in stomatal conductance (A) and bulk $\delta^{18}O$ values (B) of organically (org) and conventionally (con) grown soybean in 2017 and winter wheat in 2017 and 2018 (mean ± SE, n = 4). Bulk $\delta^{18}O$ values of soybean represent bean material, bulk $\delta^{18}O$ values of wheat represent flag leaf material. Significant differences in g_s between the treatments at specific sampling dates are indicated with asterisks (with $^*p < 0.05$, Table 5). Significant differences in g_s after statistical time-series analysis are indicated by † (with $p < 0.05$, Table 5). Differences in bulk $\delta^{18}O$ were not statistically significant (Table 6).

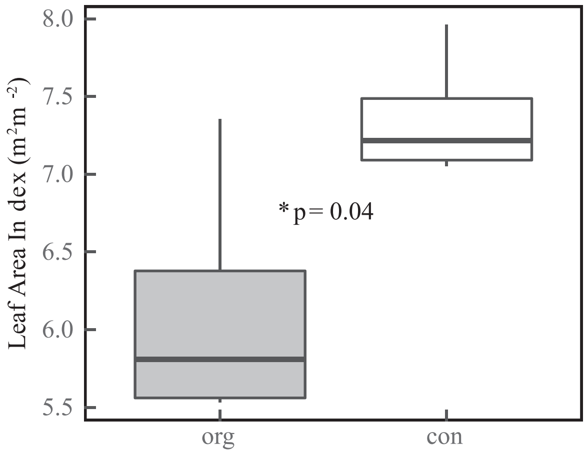

Fig. 8. Leaf area index measured in organically (org) and conventionally (con) grown winter wheat in 2020 (n = 4).

differences in hydraulic conductivity or root water uptake resulting from the different pest managements of the organic and conventional treatments were responsible for these patterns. Conventionally grown wheat received two fungicide sprayings per season, while organically grown wheat was not treated with any pesticides during 2017 and 2018 (Tab. S1). It is known that pathogens infecting xylem tissue can impair plant water transport and status, resulting in lower g_s (Berryman et al., 1991a, 1991b; Pérez-Donoso et al., 2007; Tong et al., 2016). However, this explanation is rather speculative, also because conventionally grown crops have been shown to be more vulnerable to xylem cavitation compared to organically grown crops (Sun et al., 2021a). In soybean, farming systems did not affect g_s significantly. Sun et al. (2021a) already found less pronounced effects of organic and conventional farming systems on hydraulic traits of pea compared to barley. It could therefore be that the ability of N-fixation and thus better N nutrition (Fig. S2) countervailed farming system effects on legumes also in our experiment. Nevertheless, reducing g_s and increasing the transpiration efficiency (i.e. crop mass production per unit crop transpiration) of crops is of great interest in order to maintain yields under increasingly occurring drought events (Sinclair et al., 2005; Sinclair, 2018). Thus, our results showing lower g_s of wheat under organic crop management point towards the potential of organic farming as a more sustainable and resistant farming system in a changing climate.

We analyzed the bulk $\delta^{18}O$ values of winter wheat leaves and soybean beans as an independent measure of treatment effects on g_s. $\delta^{18}O$ values in plants are driven by the $\delta^{18}O$ values of the plants' source water and the evaporative ^{18}O enrichment of leaf water (Barbour, 2007; Kahmen et al., 2008; Cernusak et al., 2016). With similar source water $\delta^{18}O$ values and identical atmospheric environments, treatment differences in $\delta^{18}O$ values can be explained by differences in g_s, where a lower g_s will lead to slightly ^{18}O enriched values (i.e. higher $\delta^{18}O$ values) in plant material (Barbour and Farquhar, 2000; Scheidegger et al., 2000; Grams et al., 2007). Our analysis revealed no statistical difference between the treatments but a tendency towards more positive and thus enriched $\delta^{18}O$ values in the organic treatments compared to the conventional treatments (Fig. 7b). This trend supports our earlier finding of lower g_s in wheat and the similar tendency of soybean growing under the organic treatments. It has to be considered, however, that the magnitude of the effect of g_s on $\delta^{18}O$ values in plant material is relatively small compared to the naturally occurring variability of $\delta^{18}O$ values in plant

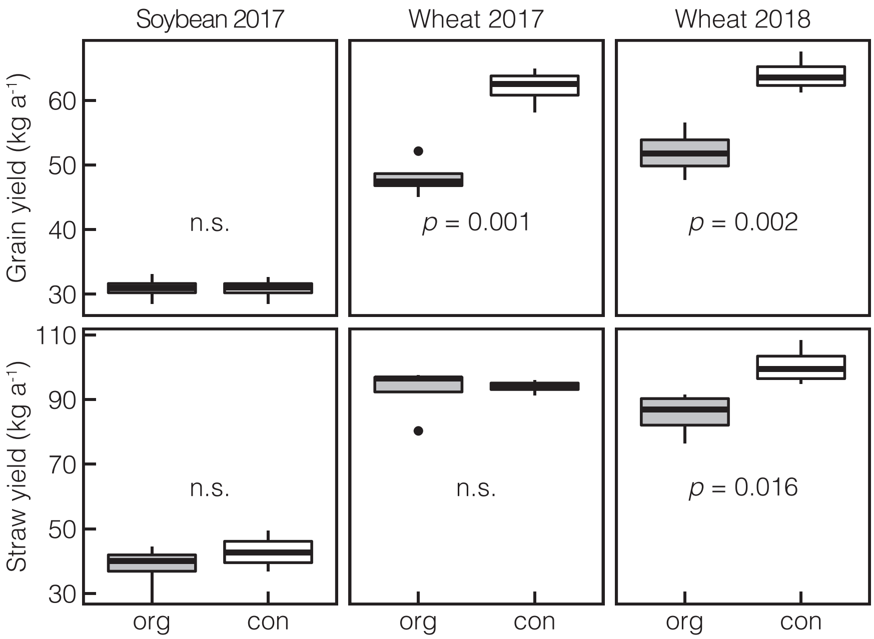

Fig. 9. Straw and grain dry matter yield of winter wheat and soybean of the year 2017 and 2018, compared between the treatments organic (org) and conventional (con) (n = 4). This figure is based on data that has been gratefully received from Agroscope Reckenholz, Switzerland (unpublished).

Table 4
ANOVA of linear mixed-effect modelled time series analyses of estimated root water uptake (RUD) depths derived from $\delta^{18}O$ values of soil and xylem water. Formula in R: lme(WUD ~ treatment *time, random = ~1| plot, method = "REML", data). a) was obtained by day-specific t-tests and by counting the days where treatment was significant ($p < 0.05$).

Species	Coefficient	numDF	denDF	F-value	*p*-value	Nr. of days significant[a])
Soybean 2017	treatment	1.00	6.00	3.41	0.115	0
	treatment: time	7.00	41.00	0.18	0.987	
Winter wheat 2017	treatment	1.00	6.00	0.36	0.570	0
	treatment: time	5.00	30.00	0.31	0.905	
Winter wheat 2018	treatment	1.00	6.00	0.34	0.582	0
	treatment: time	7.00	42.00	0.81	0.583	

material from crops grown under identical conditions (Cueni et al., 2021).

4.3. Implications for total water use

Transpiration accounts for the major part of water use in agronomic systems (Jeanguenin et al., 2017). Transpiration per unit leaf area is determined by stomatal conductance and the leaf to air vapor pressure deficit (VPD) (Ehleringer et al., 1993). Since VPD should be similar between our treatments, lower g_s observed in organically compared to conventionally grown wheat suggests lower water use of organic wheat on a per leaf area basis. For an assessment at the ecosystem level, transpiration rates per unit leaf area need to be scaled by the total leaf area, or the leaf area index (LAI) in a field or ecosystem. While leaf area was not determined for soybean, we found leaf area to be significantly lower for winter wheat in the organic compared to the conventional treatment (Fig. 8, Table 6). We also found that winter wheat has a lower grain yield and lower or similar straw yield in the organic compared to the conventional treatment (Fig. 9, Table 6). Reduced g_s in combination with lower leaf area and/or lower biomass thus suggests that the total water use of winter wheat was indeed lower in the organic compared to the conventional treatment not only on a per leaf area scale but also on the whole plant and ecosystem scale. For soybean we found a tendency for lower g_s in the organic system while both treatments showed similar grain and straw yields. Thus, we can say that treatment effects on water use of soybean per unit leaf area point towards the same direction but are likely to be smaller compared to the effects observed in wheat. However, LAI measurements would also here be necessary to account for water use above unit leaf area levels.

Based on these findings combined with the observed absence of a difference in soil water retention capacity between the treatments we propose that the higher soil moisture availability observed particularly in the rooting horizon of wheat in 2018 could be the result of an overall lower water use of wheat in the organic compared to the conventional treatment. This implies that organic farming might not only reduce the environmental impact of agriculture with regard to pesticide use, soil fertility, greenhouse gas emissions and biodiversity, but could also be a water saving farming strategy. In regard to climate change, this may be a

Table 5
ANOVA of linear mixed-effect modelled time series analyses of stomatal conductance (g_s). Formula in R: lme(variable ~ treatment*time, random = ~1| plot, method = "REML", data). a) was obtained by day-specific t-tests and by counting the days where treatment differences were statistically significant ($p < 0.05$).

Variable	Species	Coefficient	numDF	denDF	F-value	*p*-value	Nr. of days significant[a])
g_s	Soybean 2017	treatment	1.00	6.00	0.86	0.391	0
		treatment:time	5.00	30.00	1.35	0.270	
	Winter wheat 2017	treatment	1	6	9.21	**0.023**	0
		treatment:time	4	23	1.56	0.219	
	Winter wheat 2018	treatment	1.00	6.00	6.34	**0.045**	1
		treatment:time	6.00	36.00	1.10	0.381	

Table 6
Student's t-tests evaluating treatment differences in bulk δ^{18}O values of soybean beans and wheat flag leaves, in LAI, and in straw and grain dry matter yield of winter wheat and soybean (n = 4).

Variable	Species / Season	Coefficient	Estimate	Std. error	t-value	*p*-value	R^2
Bulk δ^{18}O	Soybean 2017	treatment	-0.45	0.37	-1.21	0.273	0.20
	Winter wheat 2017	treatment	-0.44	0.21	-2.12	0.079	0.43
	Winter wheat 2018	treatment	-0.15	0.23	-0.65	0.542	-0.09
LAI	Winter wheat 2017	treatment	1.21	0.48	2.60	**0.041**	0.45
Straw yield	Soybean 2017	treatment	4.21	4.10	1.03	0.344	0.15
	Winter wheat 2017	treatment	1.23	4.27	0.29	0.783	0.01
	Winter wheat 2018	treatment	15.08	4.54	3.32	**0.016**	0.59
Grain yield	Soybean 2017	treatment	-0.07	1.28	-0.05	0.959	0.00
	Winter wheat 2017	treatment	14.00	2.08	6.74	**0.001**	0.88
	Winter wheat 2018	treatment	12.01	2.32	5.17	**0.002**	0.79

crucial advantage in coping with future drought events. Organically managed crops have already been suggested to be more drought resistant with organic crops outyielding conventional crops under drought (Lotter et al., 2003; Pimentel and Burgess, 2014). Until now, however, this effect was mainly related to higher soil water holding capacities in organic compared to conventional soils (Lockeretz et al., 1981; Stanhill, 1990; Lotter et al., 2003; Pimentel and Burgess, 2014). Here we suggest that the lower water use we observed in organically grown wheat (and possibly also soybean) may contribute to less rapidly depleted soil water storages and thus points to the potential of organic agriculture in constituting a more water saving strategy compared to conventional farming.

Although our study gives exciting first evidence that organically grown crops might use less water than conventionally used crops per unit area, our study does not allow to compare the water use of both farming systems per unit crop yield. Given that organically managed systems have typically yields that are 5–34% lower than conventionally managed systems (Mäder et al., 2002; Seufert et al., 2012), it would be necessary to quantify the cumulative water use of a farming system throughout a growing season. This cumulative water use can then be related to crop yields in organically and conventionally managed systems. This analysis would then reveal if the water savings that we describe here on an area basis also scale to water saving effects per unit crop yield.

5. Conclusive Summary

Comparing the water relations of organically with conventionally managed agricultural systems we found no differences in water retention and evaporative soil water losses between the two systems. Instead, lower stomatal conductance and reduced leaf area observed in organically managed wheat led to consistently higher soil moisture in the rooting zone of the plant which points to lower water use in organically compared to conventionally managed farming systems. Treatment effects on soybean were not as pronounced as in wheat but the observed trends were similar for the two species. Importantly, the observed ecohydrological differences between the two farming systems were often small compared to the inherent variability in the data of the response variables. This illustrates the methodological challenges that are associated with studies as we present here. Yet, even small differences in soil moisture content, stomatal conductance and leaf area can make a difference when scaled to the field or landscape level. Our results therefore imply possible advantages of organic farming regarding agronomic water use as well as for the resistance of farming systems to current or future drought scenarios. Future work should quantify and compare the seasonal water uses of organically managed crops to assess the potential of organic farming in saving water use under different environmental conditions and different crop varieties when standardized to unit crop yield.

Declaration of Competing Interest

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

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.agee.2022.107915.

References

Abdi, E., Babapour, S., Majnounian, B., Amiri, G.Z., Deljouei, A., 2018. How does organic matter affect the physical and mechanical properties of forest soil? J. For. Res. 29, 657–662.

Abdullah, A.S., 2014. Minimum tillage and residue management increase soil water content, soil organic matter and canola seed yield and seed oil content in the semiarid areas of Northern Iraq. Soil Tillage Res. 144, 150–155. https://doi.org/10.1016/j.still.2014.07.017.

Al-Karaki, G.N., 1998. Benefit, cost and water-use efficiency of arbuscular mycorrhizal durum wheat grown under drought stress. Mycorrhiza 8, 41–45. https://doi.org/10.1007/s005720050209.

Amooh, M.K., Bonsu, M., 2015. Effects of soil texture and organic matter on evaporative loss of soil moisture. JOGAE 3 (3), 152–161.

Barbeta, A., Gimeno, T.E., Clavé, L., Fréjaville, B., Jones, S.P., Delvigne, C., Wingate, L., Ogée, J., 2020. An explanation for the isotopic offset between soil and stem water in a temperate tree species. New Phytol. 227, 766–779. https://doi.org/10.1111/nph.16564.

Barbour, M.M., 2007. Stable oxygen isotope composition of plant tissue: a review. Funct. Plant Biol. 34, 83–94. https://doi.org/10.1071/fp06228.

Barbour, M.M., Farquhar, G.D., 2000. Relative humidity- and ABA-induced variation in carbon and oxygen isotope ratios of cotton leaves. Plant Cell Environ. 23, 473–485. https://doi.org/10.1046/j.1365-3040.2000.00575.x.

Barnard, R.L., de Bello, F., Gilgen, A.K., Buchmann, N., 2006. Theδ18O of root crown water best reflects source waterδ18O in different types of herbaceous species. Rapid Commun. Mass Spectrom. 20, 3799–3802.

Bengtsson, J., Ahnström, J., Weibull, A.C., 2005. The effects of organic agriculture on biodiversity and abundance: a meta-analysis. J. Appl. Ecol. 42 (2), 261–269.

Bennett, E.M., Carpenter, S.R., Caraco, N.F., 2001. Human impact on erodable phosphorus and eutrophication: A global perspective. BioScience 51, 227–234.

Berryman, C.A., Eamus, D., Farrar, J.F., 1991a. The hydraulic conductivity of roots of rust-infected barley seedlings. Physiol. Mol. Plant Pathol. 38, 407–415.

Berryman, C.A., Eamus, D., Farrar, J.F., 1991b. Water relations of leaves of barley infected with brown rust. Physiol. Mol. Plant Pathol. 38, 393–405.

Besson, J.-M., Niggli, U., 1991. DOK-Versuch: Vergleichende Langzeit Untersuchungen in den drei Anbausystemen biologisch-Dynamisch, Organisch-biologisch und Konventionell. I. Konzeption des DOK-Versuchs: 1. und 2. Fruchtfolgeperiode. Schweiz. Landwirtsch. Forsch. 31, 79–109.

Brinkmann, N., Seeger, S., Weiler, M., Buchmann, N., Eugster, W., Kahmen, A., 2018. Employing stable isotopes to determine the residence times of soil water and the temporal origin of water taken up by Fagus sylvatica and Picea abies in a temperate forest. New Phytol. 219, 1300–1313.

Broadley, M.R., Escobar-Gutiérrez, A.J., Burns, A., Burns, I.G., 2001. Nitrogen-limited growth of lettuce is associated with lower stomatal conductance. New Phytol. 152, 97–106.

Calderini, D.F., Dreccer, M.F., Slafer, G.A., 1997. Consequences of breeding on biomass, radiation interception and radiation-use efficiency in wheat. Field Crop. Res 52, 271–281. https://doi.org/10.1016/s0378-4290(96)03465-x.

Cates, A.M., Ruark, M.D., Hedtcke, J.L., Posner, J.L., 2016. Long-term tillage, rotation and perennialization effects on particulate and aggregate soil organic matter. Soil Tillage Res. 155, 371–380.

Cernusak, L.A., Barbour, M.M., Arndt, S.K., Cheesman, A.W., English, N.B., Feild, T.S., Helliker, B.R., Holloway-Phillips, M.M., Holtum, J.A.M., Kahmen, A., McInerney, F. A., Munksgaard, N.C., Simonin, K.A., Song, X., Stuart-Williams, H., West, J.B., Farquhar, G.D., 2016. Stable isotopes in leaf water of terrestrial plants. Plant Cell Environ. 39, 1087–1102. https://doi.org/10.1111/pce.12703.

Chaves, M.M., Maroco, J.P., Pereira, J.S., 2003. Understanding plant responses to drought — from genes to the whole plant. Funct. Plant Biol. 30, 239–264.

Chen, Y., Helliker, B.R., Tang, X., Li, F., Zhou, Y., Song, X., 2020. Stem water cryogenic extraction biases estimation in deuterium isotope composition of plant source water. Proc. Natl. Acad. Sci. U.S.A. 117, 33345–33350. https://doi.org/10.1073/pnas.2014422117.

Clark, I.D., Fritz, P., 1997. Environmental Isotopes in Hydrogeology, first ed. CRC Press. https://doi.org/10.1201/9781482242911.

Cooper, J., Baranski, M., Stewart, G., Lange, M.N., Bàrberi, P., Fließbach, A., Peigné, J., Berner, A., Brock, C., Casagrande, M., Crowley, O., David, C., Vliegher, A.D., Döring, T.F., Dupont, A., Entz, M., Grosse, M., Haase, T., Halde, C., Hammerl, V., Huiting, H., Leithold, G., Messmer, M., Schloter, M., Sukkel, W., Heijden, M.G.A., van der, Willekens, K., Wittwer, R., Mäder, P., 2016. Shallow non-inversion tillage in organic farming maintains crop yields and increases soil C stocks: a meta-analysis. Agron. Sustain. Dev. 36, 22. https://doi.org/10.1007/s13593-016-0354-1.

Cueni, F., Nelson, D.B., Kahmen, A., 2021. Effects of phenotypic variability on the oxygen and hydrogen isotope compositions of grains in different winter wheat varieties. Isot. Environ. Health Sci. 1–21. https://doi.org/10.1080/10256016.2021.2002855.

Dawson, T.E., Hahm, W.J., Crutchfield-Peters, K., 2020. Digging deeper: what the critical zone perspective adds to the study of plant ecophysiology. New Phytol. 226, 666–671. https://doi.org/10.1111/nph.16410.

De, R., Giri, G., Saran, G., Singh, R.K., Chaturvedi, G.S., 1982. Modification of water balance of dryland wheat through the use of chlormequat chloride. J. Agric. Sci. 98, 593–597.

Di Prima, S., Rodrigo-Comino, J., Novara, A., Iovino, M., Pirastru, M., Keesstra, S., Cerdà, A., 2018. Soil physical quality of citrus orchards under tillage, herbicide, and organic managements. Pedosphere 28, 463–477.

Dimitri, C., Greene, C., 2002. Recent growth patterns in the U.S. Org. Foods Mark.

Drinkwater, L.E., Wagoner, P., Sarrantonio, M., 1998. Legume-based cropping systems have reduced carbon and nitrogen losses. Nature 396, 262–265.

Edwards, W.M., Shipitalo, M.J., Owens, L.B., Norton, L.D., 1990. Effect of Lumbricus terrestris L. burrows on hydrology of continuous no-till corn fields. Geoderma 46, 73–84.

Ehleringer, J.R., Dawson, T.E., 1992. Water uptake by plants: perspectives from stable isotope composition. Plant, Cell Environ. 15, 1073–1082.

Ehleringer, J.R., Hall, A.E., Farquhar, G.D., 1993. Stable isotopes and plant carbon-water relation. In: Introduction: Water Use in Relation to Productivity. Academic Press, pp. 3–8. https://doi.org/10.1016/b978-0-08-091801-3.50007-6.

Eurostat, 2019. Organic crop area by agricultural production methods and crops (from 2012 onwards). http://appsso.eurostat.ec.europa.eu/nui/submitViewTableAction.do abgerufen.

Evers, J.B., Huth, N.I., Renton, M., 2009. Light Extinction in Spring Wheat Canopies in Relation to Crop Configuration and Solar Angle. In: Proceedings of the Third Int Symposium Plant Growth Model Simul Vis Appl 107–110. https://doi.org/10.1109/pma.2009.20.

Fang, X., Li, Y., Nie, J., Wang, C., Huang, K., Zhang, Y., Zhang, Y., She, H., Liu, X., Ruan, R., et al., 2018. Effects of nitrogen fertilizer and planting density on the leaf photosynthetic characteristics, agronomic traits and grain yield in common buckwheat (Fagopyrum esculentum M.). Field Crop. Res. 219, 160–168.

Fließbach, A., Oberholzer, H.-R., Gunst, L., Mäder, P., 2007. Soil organic matter and biological soil quality indicators after 21 years of organic and conventional farming. Agric. Ecosyst. Environ. 118, 273–284. https://doi.org/10.1016/j.agee.2006.05.022.

Forster, D., Andres, C., Verma, R., Zundel, C., Messmer, M.M., Mäder, P., 2013. Yield and economic performance of organic and conventional cotton-based farming systems–results from a field trial in India. PLoS One 8, e81039.

Freyberg, J., Allen, S.T., Grossiord, C., Dawson, T.E., 2020. Plant and root-zone water isotopes are difficult to measure, explain, and predict: Some practical recommendations for determining plant water sources. Methods Ecol. Evol. 11, 1352–1367. https://doi.org/10.1111/2041-210x.13461.

Gattinger, A., Muller, A., Haeni, M., Skinner, C., Fliessbach, A., Buchmann, N., Mäder, P., Stolze, M., Smith, P., Scialabba, N.E.H., Niggli, U., 2012. Enhanced top soil carbon stocks under organic farming. Proc. Natl. Acad. Sci. U.S.A. 109 (44), 18226–18231.

Gehre, M., Geilmann, H., Richter, J., Werner, R.A., Brand, W.A., 2004. Continuous flow ^{2}H/^{1}H and ^{18}O/^{16}O analysis of water samples with dual inlet precision. Rapid communications in mass spectrometry 18 (22), 2650–2660. https://doi.org/10.1002/rcm.1672.

Gomiero, T., Pimentel, D., Paoletti, M.G., 2011. Is there a need for a more sustainable agriculture? Crit. Rev. Plant Sci. 30, 6–23.

Grams, T.E.E., Kozovits, A.R., Häberle, K., Matyssek, R., Dawson, T.E., 2007. Combining δ13C and δ18O analyses to unravel competition, CO$_2$ and O3 effects on the physiological performance of different-aged trees. Plant Cell Environ. 30, 1023–1034. https://doi.org/10.1111/j.1365-3040.2007.01696.x.

Hole, D.G., Perkins, A.J., Wilson, J.D., Alexander, I.H., Grice, P.V., Evans, A.D., 2005. Does organic farming benefit biodiversity? Biol. Conserv. 122 (1), 113–130.

Jeanguenin, L., Mir, A.P., Chaumont, F., 2017. Uptake, Loss and Control. In: Thomas, Brian, Murray, Brian G., Murphy, Denis J. (Eds.), Encyclopedia of Applied Plant Sciences, , 2nd1. Academic Press, pp. 135–140.

Kahmen, A., Simonin, K., Tu, K.P., Merchant, A., Callister, A., Siegwolf, R., Dawson, T.E., Arndt, S.K., 2008. Effects of environmental parameters, leaf physiological properties and leaf water relations on leaf water δ18O enrichment in different Eucalyptus species. Plant Cell Environ. 31, 738–751. https://doi.org/10.1111/j.1365-3040.2008.01784.x.

Krause, H.M., Fliessbach, A., Mayer, J., Mäder, P., 2020. Implementation and management of the DOK long-term system comparison trial. Long-Term Farming Systems Research. Academic Press, pp. 37–51.

Kundel, D., Bodenhausen, N., Jørgensen, H.B., Truu, J., Birkhofer, K., Hedlund, K., Mäder, P., Fliessbach, A., 2020. Effects of simulated drought on biological soil quality, microbial diversity and yields under long-term conventional and organic agriculture. FEMS Microbiol. Ecol. https://doi.org/10.1093/femsec/fiaa205.

Li, R., Li, Q., Pan, L., 2020. Review of organic mulching effects on soil and water loss. Arch. Agron. Soil Sci. 67, 1–16. https://doi.org/10.1080/03650340.2020.1718111.

Liebig, M.A., Doran, J.W., 1999. Impact of organic production practices on soil quality indicators. J. Environ. Qual. 28, 1601–1609.

Lin, B.B., 2010. The role of agroforestry in reducing water loss through soil evaporation and crop transpiration in coffee agroecosystems. Agric. For. Meteor. 150, 510–518. https://doi.org/10.1016/j.agrformet.2009.11.010.

Lockeretz, W., Shearer, G., Kohl, D.H., 1981. Organic farming in the corn belt. Science 211, 540–547. https://doi.org/10.1126/science.211.4482.540.

Lotter, D.W., Seidel, R., Liebhardt, W., 2003. The performance of organic and conventional cropping systems in an extreme climate year. Am. J. Altern. Agric. 18, 146–154. https://doi.org/10.1079/ajaa200345.

Mäder, P., Edenhofer, S., Boller, T., Wiemken, A., Niggli, U., 2000. Arbuscular mycorrhizae in a long-term field trial comparing low-input (organic, biological) and high-input (conventional) farming systems in a crop rotation. Biol. Fertil. Soils 31, 150–156.

Mäder, P., Fließbach, A., Dubois, D., Gunst, L., Fried, P., Niggli, U., 2002. Soil fertility and biodiversity in organic farming. Science 296, 1694–1697. https://doi.org/10.1126/science.1071148.

McLaughlin, A., Mineau, P., 1995. The impact of agricultural practices on biodiversity. Agric. Ecosyst. Environ. 55, 201–212.

Meinzer, F.C., Andrade, J.L., Goldstein, G., Holbrook, N.M., Cavelier, J., Wright, S.J., 1999. Partitioning of soil water among canopy trees in a seasonally dry tropical forest. Oecologia 121, 293–301. https://doi.org/10.1007/s004420050931.

de Mendiburu, F., 2017. agricolae: Statistical Procedures for Agricultural Research. R package version 1.2–8. https://CRAN.R-project.org/package=agricolae.

Monsi, M., Saeki, T., 1953. On the factor light in plant communi-ties and its importance for matter production. Jpn. J. Bot. 14, 22–52.

Mueller, M.H., Alaoui, A., Kuells, C., Leistert, H., Meusburger, K., Stumpp, C., Weiler, M., Alewell, C., 2014. Tracking water pathways in steep hillslopes by δ18O depth profiles of soil water. J. Hydrol. 519, 340–352. https://doi.org/10.1016/j.jhydrol.2014.07.031.

Newberry, S.L., Nelson, D.B., Kahmen, A., 2017a. Cryogenic vacuum artifacts do not affect plant water-uptake studies using stable isotope analysis. Ecohydrology 10, e1892.

Newberry, S.L., Prechsl, U.E., Pace, M., Kahmen, A., 2017b. Tightly bound soil water introduces isotopic memory effects on mobile and extractable soil water pools. Isot. Environ. Health Stud. 53, 368–381. https://doi.org/10.1080/10256016.2017.1302446.

Oades, J.M., 1984. Soil organic matter and structural stability: mechanisms and implications for management. Biological Processes and Soil Fertility. Springer, Netherlands, Dordrecht, pp. 319–337.

Ohu, J.O., Raghavan, G., McKyes, E., 1985. Peatmoss effect on the physical and hydraulic characteristics of compacted soils. Trans. ASAE 28, 420–424.

Orlowski, N., Breuer, L., McDonnell, J.J., 2016. Critical issues with cryogenic extraction of soil water for stable isotope analysis. Ecohydrology 9, 1–5. https://doi.org/10.1002/eco.1722.

Orlowski, N., Breuer, L., Angeli, N., Boeckx, P., Brumbt, C., Cook, C.S., Dubbert, M., Dyckmans, J., Gallagher, B., Gralher, B., Herbstritt, B., Hervé-Fernández, P., Hissler, C., Koeniger, P., Legout, A., Macdonald, C.J., Oyarzún, C., Redelstein, R., Seidler, C., Siegwolf, R., Stumpp, C., Thomsen, S., Weiler, M., Werner, C., McDonnell, J.J., 2018. Inter-laboratory comparison of cryogenic water extraction systems for stable isotope analysis of soil water. Hydrol. Earth Syst. Sci. 22, 3619–3637. https://doi.org/10.5194/hess-22-3619-2018.

Peigné, J., Casagrande, M., Payet, V., David, C., Sans, F.X., Blanco-Moreno, J.M., Cooper, J., Gascoyne, K., Antichi, D., Bàrberi, P., Bigongiali, F., Surböck, A., Kranzler, A., Beeckman, A., Willekens, K., Luik, A., Matt, D., Grosse, M., Heß, J., Clerc, M., Dierauer, H., Mäder, P., 2016. How organic farmers practice conservation agriculture in Europe. Renew. Agric. Food Syst. 31, 72–85. https://doi.org/10.1017/s1742170514000477.

Penna, D., Hopp, L., Scandellari, F., Allen, S.T., Benettin, P., Beyer, M., Geris, J., Klaus, J., Marshall, J.D., Schwendenmann, L., Volkmann, T.H.M., Freyberg, J., von, Amin, A., Ceperley, N., Engel, M., Frentress, J., Giambastiani, Y., McDonnell, J.J., Zuecco, G., Llorens, P., Siegwolf, R.T.W., Dawson, T.E., Kirchner, J.W., 2018. Ideas and perspectives: tracing terrestrial ecosystem water fluxes using hydrogen and oxygen stable isotopes – challenges and opportunities from an interdisciplinary perspective. Biogeosciences 15, 6399–6415. https://doi.org/10.5194/bg-15-6399-2018.

Pérez-Donoso, A.G., Greve, L.C., Walton, J.H., Shackel, K.A., Labavitch, J.M., 2007. Xylella fastidiosa infection and ethylene exposure result in xylem and water movement disruption in grapevine shoots. Plant Physiol. 143, 1024–1036. https://doi.org/10.1104/pp.106.087023.

Pimentel, D., 2005. Environmental and economic costs of the application of pesticides primarily in the United States. Environ. Dev. Sustain. 7, 229–252.

Pimentel, D., Burgess, M., 2014. Integrated pest management. Pestic. Probl. Vol.3, 141–166. https://doi.org/10.1007/978-94-007-7796-5_6.

Pimentel, D., Harvey, C., Resosudarmo, P., Sinclair, K., Kurz, D., McNair, M., Crist, S., Shpritz, L., Fitton, L., Saffouri, R., et al., 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267, 1117–1123.

Pimentel, D., Hepperly, P., Hanson, J., Douds, D., Seidel, R., 2005. Environmental, energetic, and economic comparisons of organic and conventional farming systems. BioScience 55, 573.

Pinheiro, J., Bates, D., DebRoy, S., Sarkar and R Core Team, 2018. nlme: Linear and Nonlinear Mixed Effects Models. R package version 3.1–137. https://CRAN.R-project.org/package=nlme.

Pinheiro, J.C., Bates, D.M., 2011. Mixed-effects Models in S and S-PLUS.

Prechsl, Ulrich E., Gilgen, Anna K., Kahmen, Ansgar, Buchmann, Nina, 2014. Reliability and quality of water isotope data collected with a low-budget rain collector. Rapid Communications in Mass Spectrometry 28 (8), 879–885. https://doi.org/10.1002/rcm.6852.

R Core Team, 2017. R: A Language and Environment for Statistical Computing. R Foundation for Statistical Computing, Vienna, Austria.

Radin, J.W., Parker, L.L., Guinn, G., 1982. Water relations of cotton plants under nitrogen deficiency: V. environmental control of abscisic acid accumulation and stomatal sensitivity to abscisic acid. Plant Physiol. 70, 1066–1070.

Rawls, W.J., Pachepsky, Y.A., Ritchie, J.C., Sobecki, T.M., Bloodworth, H., 2003. Effect of soil organic carbon on soil water retention. Geoderma 116, 61–76. https://doi.org/10.1016/s0016-7061(03)00094-6.

Reganold, J.P., Wachter, J.M., 2016. Organic agriculture in the twenty-first century. Nat. Plants 2, 1–8.

Reganold, J.P., Palmer, A.S., Lockhart, J.C., Macgregor, A.N., 1993. Soil quality and financial performance of biodynamic and conventional farms in new zealand. Science 260, 344–349.

Reganold, J.P., Glover, J.D., Andrews, P.K., Hinman, H.R., 2001. Sustainability of three apple production systems. Nature 410, 926–930.

Saxton, K.E., Rawls, W.J., 2006. Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci. Soc. Am. J. 70, 1569–1578. https://doi.org/10.2136/sssaj2005.0117.

Scheidegger, Y., Saurer, M., Bahn, M., Siegwolf, R., 2000. Linking stable oxygen and carbon isotopes with stomatal conductance and photosynthetic capacity: a conceptual model. Oecologia 125, 350–357. https://doi.org/10.1007/s004420000466.

Seufert, V., Ramankutty, N., Foley, J.A., 2012. Comparing the yields of organic and conventional agriculture. Nature 485, 229–232. https://doi.org/10.1038/nature11069.

Siegrist, S., Schaub, D., Pfiffner, L., Mäder, P., 1998. Does organic agriculture reduce soil erodibility? The results of a long-term field study on loess in Switzerland. Agric. Ecosyst. Environ. 69, 253–264.

Sinclair, T.R., 2018. Effective water use required for improving crop growth rather than transpiration efficiency. Front. Plant Sci. 9, 1442. https://doi.org/10.3389/fpls.2018.01442.

Sinclair, T.R., Hammer, G.L., Oosterom, E.J. van, 2005. Potential yield and water-use efficiency benefits in sorghum from limited maximum transpiration rate. Funct. Plant Biol. 32, 945–952. https://doi.org/10.1071/fp05047.

Spargo, J.T., Cavigelli, M.A., Mirsky, S.B., Maul, J.E., Meisinger, J.J., 2011. Mineralizable soil nitrogen and labile soil organic matter in diverse long-term cropping systems. Nutr. Cycl. Agroecosyst. 90, 253–266.

Sprenger, M., Stumpp, C., Weiler, M., Aeschbach, W., Allen, S.T., Benettin, P., Dubbert, M., Hartmann, A., Hrachowitz, M., Kirchner, J.W., McDonnell, J.J., Orlowski, N., Penna, D., Pfahl, S., Rinderer, M., Rodriguez, N., Schmidt, M., Werner, C., 2019. The demographics of water: a review of water ages in the critical zone. Rev. Geophys 57, 800–834. https://doi.org/10.1029/2018rg000633.

Stanhill, G., 1990. The comparative productivity of organic agriculture. Agric. Ecosyst. Environ. 30, 1–26. https://doi.org/10.1016/0167-8809(90)90179-h.

Stumpp, C., Maloszewski, P., 2010. Quantification of preferential flow and flow heterogeneities in an unsaturated soil planted with different crops using the environmental isotope δ18O. J. Hydrol. 394, 407–415. https://doi.org/10.1016/j.jhydrol.2010.09.014.

Sun, Q., Gilgen, A.K., Signarbieux, C., Klaus, V.H., Buchmann, N., 2021a. Cropping systems alter hydraulic traits of barley but not pea grown in mixture. Plant Cell Environ. 44, 2912–2924. https://doi.org/10.1111/pce.14054.

Sun, Q., Klaus, V.H., Wittwer, R., Liu, Y., Heijden, M.G.A., van der, Gilgen, A.K., Buchmann, N., 2021b. Water uptake patterns of pea and barley responded to drought but not to cropping systems. Biogeosci. Discuss. 2021, 1–37. https://doi.org/10.5194/bg-2021-217.

Tang, H., Zhou, J., Wang, C., 2005. Effects of soaking seeds with Chlormequat on germination, seedling growth and water use efficiency of different wheat cultivars. Agric. Res. Arid Areas 23, 29–34.

Tisdall, J.M., Oades, J.M., 1982. Organic matter and water-stable aggregates in soils. J. Soil Sci. 33, 141–163.

Tong, Y.-G., Ding, X.-X., Zhang, K.-C., Yang, X., Huang, W., 2016. Effect of the gall wasp leptocybe invasa on hydraulic architecture in eucalyptus camaldulensis plants. Front. Plant Sci. 7, 130. https://doi.org/10.3389/fpls.2016.00130.

Vogt, G., 2007. The Origins of Organic Farming. In W. Lockeretz, Organic Farming: An International History (S. 9–29). Cambridge, MA: CABI.

Wells, A.T., Chan, K.Y., Cornish, P.S., 2000. Comparison of conventional and alternative vegetable farming systems on the properties of a yellow earth in New South Wales. Agric. Ecosyst. Environ. 80, 47–60.

Wenninger, J., Beza, D.T., Uhlenbrook, S., 2010. Experimental investigations of water fluxes within the soil–vegetation–atmosphere system: stable isotope mass-balance approach to partition evaporation and transpiration. Phys. Chem. Earth Parts B C 35, 565–570. https://doi.org/10.1016/j.pce.2010.07.016.

Werner, R.A., Brand, W.A., 2001. Referencing strategies and techniques in stable isotope ratio analysis. Rapid Commun. Mass Spectrom. 15, 501–519.

Wheeler, S.A., Zuo, A., Loch, A., 2015. Watering the farm: Comparing organic and conventional irrigation water use in the Murray-Darling Basin, Australia. Ecol. Econ. 112, 78–85.

White, J.W.C., Cook, E.R., Lawrence, J.R., S, B.W., 1985. The DH ratios of sap in trees: implications for water sources and tree ring DH ratios. Geochim. Cosmochim. Acta 49, 237–246. https://doi.org/10.1016/0016-7037(85)90207-8.

Wickham, H., 2016. ggplot2: Elegant Graphics for Data Analysis. Springer-Verlag, New York. ISBN 978-3-319-24277-4. ⟨https://ggplot2.tidyverse.org⟩.

Willer, H., Lernoud, J., 2019. The world of organic agriculture. Stat. Emerg. Trends 2019, 1–336 (Research Institute of Organic Agriculture FiBL and IFOAM Organics International).

WWAP (UNESCO World Water Assessment Programme), 2019. The United Nations World Water Development Report 2019: Leaving No One Behind. Paris, UNESCO.

Wythers, K.R., Lauenroth, W.K., Paruelo, J.M., 1999. Bare-soil evaporation under semiarid field conditions. Soil Sci. Soc. Am. J. 63, 1341–1349. https://doi.org/10.2136/sssaj1999.6351341x.

Zhao, L., Wang, L., Cernusak, L.A., Liu, X., Xiao, H., Zhou, M., Zhang, S., 2016. Significant difference in hydrogen isotope composition between xylem and tissue water in populus euphratica. Plant Cell Environ. 39, 1848–1857. https://doi.org/10.1111/pce.12753.

Zimmermann, U., Ehhalt, D., Munnich, K.O., 1967. Soil–water movement and evapotranspiration: Changes in the isotopic composition of the water. In: Proceedings of the Symposium of Isotopes in Hydrology, Vienna 1966, IAEA, Vienna, Austria, pp. 567–584.