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DROUGHT STRESS

Water dynamics of cover crops: No evidence for relevant water input through occult precipitation

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Abstract

Rising temperatures and disruption of rainfall patterns due to climate change make water a limiting growth factor even in regions of temperate climates. Thus, producing 'more crop per drop' is of utmost importance. While cover crops provide many benefits to cropping systems, their influence on soil water is discussed controversially. While an increase in transpiration can lead to soil water depletion, the reduction of evaporation in combination with possible additional water inputs could provide a water benefit for a succeeding crop. Occult precipitation could be such an additional water input. The objective of this study was to quantify whether cover crops provide a net water benefit over a bare fallow due to the occurrence of occult precipitation. In a 2-year experiment, seven different cover crops were cultivated in pure stands and as a mixture under semi-controlled conditions in a container experiment. Water fluxes and meteorological conditions were closely monitored. Although favourable conditions occurred during both vegetation periods, we found no evidence of occult precipitation. In autumn, soil water was depleted by fast-growing cover crops. In winter, soil water was recharged due to the early preparation of a mulch layer combined with high winter precipitation while in early spring rising temperatures increased transpiration losses of a winter-hardy cover crop, leading to a reduction of soil water. For middle European conditions, this shows that (1) living cover crops do not provide any water benefits and that (2) soil water recharge in winter is highly dependent on meteorological conditions and cover crop management. From a water budget viewpoint, negative effects on a succeeding cash crop can only be prevented if cover crops are terminated early enough for replenishment of soil water.

KEYWORDS
bare fallow, catch crop, evapotranspiration, mulch

Key Points

- Can occult precipitation counteract water depletion by cover crops?
- Quantification of water fluxes in a 2-year cover crop container experiment under semi-controlled conditions.
- No occurrence of relevant amounts of occult precipitation.

- Depletion of soil water in autumn.
- Mulching can support the replenishment of soil water when winter precipitation is high.

1 | INTRODUCTION

Catch crops – also known as cover crops – are primarily grown to prevent nutrient leaching during times of high precipitation (Kaye & Quemada, 2017; Thorup-Kristensen & Nielsen, 1998). By incorporating the plant into the soil as green manure, the nutrients are returned to the soil and can be used by a succeeding crop (Dinesh et al., 2001; Langelier et al., 2021; Torstensson & Aronsson, 2000). Further benefits of cover crops are improvements in biological, chemical and physical soil properties (Blanco-Canqui & Ruis, 2020; Dabney et al., 2001; Delgado, 1998; Haruna & Nkongolo, 2015).

Since agriculture is highly dependent on favourable growth conditions, the effects of climate change on temperature as well as on global and regional rainfall patterns affect agricultural productivity. Although different meteorological simulations predict that average annual precipitation will remain constant in the future, dry periods without rainfall are projected to become longer while the intensity of precipitation events is likely to increase (IPCC, 2022; Trenberth, 2011).

Especially the overlap of critical, water-dependent growth stages of grain crops with periods of low precipitation and high temperatures is a major concern for farmers on a global scale (Mase et al., 2017; Woods et al., 2017; Zinngrebe et al., 2017). Considering these developments, water – which has already been a growth-limiting factor in the past – is predicted to become even more so in the future (Trnka et al., 2011). Thus, notwithstanding the benefits of cover crops on different soil properties and nutrient cycling efficiency of cropping systems (Selzer & Schubert, 2021), farmers are concerned that the vigorous growth of cover crops will lead to the depletion of soil water, thereby increasing drought stress for the main crop (Basche et al., 2016; McGuire et al., 1998). Nielsen et al. (2016) have reported a grain yield reduction of 3%–40% in the Great Plains after cover crop cultivation due to lower water availability than after a fallow.

The main water fluxes in cropping systems include water losses due to (1) transpiration, (2) evaporation and (3) leaching and water gains in the form of (1) precipitation, (2) irrigation and (3) occult precipitation (Datta et al., 2021; Matos et al., 2022).

Most of the studies with cover crops have focused on water losses caused by evaporation and transpiration. While cover crops increase transpiration losses, they can reduce evaporation in comparison to fallow soil when used as a mulch layer (Bodner et al., 2011; Campiglia et al., 2011; Meyer et al., 2019; Pedrosa De Azevedo et al., 1999; Qi et al., 2011; Unger & Vigil, 1998). The studies show contradictory results as to whether the reduction of evaporation outweighs the increased transpiration losses depending on the duration of the vegetation period, cover crop species (winter-hardy vs. frost-sensitive) and meteorological growth conditions.

In this study, next to exploring evaporation and transpiration losses of various cover crops, we explored possible additional water gains by quantifying relevant water fluxes in a semi-controlled environment. It has been shown that when atmospheric humidity is high, the condensation and coalescence of water droplets on plant surfaces can cause stemflow generation independent of precipitation. This process of 'fog combing' or 'occult precipitation', that is precipitation which is not detected by standard rain gauges (Holwerda et al., 2010), has been described for different locations around the world. In rainforests, it can amount to up to 5%–20% of gross precipitation (Remmert, 2013). In Californian redwood forests, occult precipitation accounted for 34% of the total annual water input in comparison to 17% when trees were absent (Dawson, 1998). Plants in semi-arid regions and deserts are specialized in using fog combing to meet their water demand in a highly strenuous environment (Ebner et al., 2011). The magnitude of these fluxes, independent of geographic location, is determined by (1) meteorological conditions such as humidity, precipitation, atmospheric temperature and wind speed (Van Stan et al., 2014) and (2) crop-specific parameters. The latter include plant height and architecture, leaf morphology (i.e. diameter and length-to-width ratio), leaf area index (LAI), leaf surface roughness and the chemical composition of the leaf surface (Ebner et al., 2011; Holloway, 1970; Mali et al., 2020).

While changes in soil physical properties through cover cropping have been studied extensively to explain changes in soil water dynamics (i.e., Blanco-Canqui & Ruis, 2020; Irmak et al., 2011; Steele et al., 2012), the possibility that cover crops could positively affect water inputs through occult precipitation has not been considered yet.

The typical growing season for cover crops in middle Europe starts at the end of August and lasts until the cultivation of a main crop in the following year. This period, especially the months in late autumn and winter, is characterized by relatively high atmospheric humidity and low temperatures (PIK, 2020), providing optimum meteorological conditions for the occurrence of occult precipitation (Zimmermann & Zimmermann, 2002).

We hypothesized that under middle European climatic conditions cover crops to increase the water input from the atmosphere into the soil through occult precipitation in comparison to a bare fallow control. We furthermore hypothesized that the effect would be more pronounced for non-transpiring (artificial) plants than for transpiring cover crops.

It has been shown previously that the management of cover crops, especially the timing of cover crop termination, plays an important role in soil moisture dynamics (Alonso-Ayuso et al., 2014, 2018). Mulching of cover crops is an effective tool to increase soil moisture through the reduction of evaporation and the termination of transpiration (Chalise et al., 2019; Ji & Unger, 2001). At the same time, winter-hardy cover crops may increase water losses in spring when radiation intensity and temperature increase, thereby promoting transpiration (Qi et al., 2011). This can cause soil water depletion and hamper the development of a succeeding crop. We hypothesized that soil moisture can be recharged during winter when frost-sensitive cover crops are mulched after the first frost event while winter-hardy cover crops depletes soil water in early spring.

2 | MATERIALS AND METHODS

2.1 | Container experiments

Cover crops were cultivated at the experimental station of the Institute of Plant Nutrition in Giessen (50°35′53.30″N, 8°40′1.56″E) in 2020 and 2021. The crops were grown in large containers (width × depth × height = 40 cm × 40 cm × 80 cm) which allowed for semi-controlled growth conditions (Selzer & Schubert, 2021). While subjected to natural variations of meteorological conditions, soil moisture was kept at a given water-holding capacity (WHC) of 50% in 2020 and 45% in 2021 through irrigation and nutrients were supplied in a mineral form to create non-limiting growth conditions. This ensured the production of maximum cover crop biomass, creating optimum conditions for maximum water inputs through occult precipitation.

Each container was filled with 130 kg limed (2.5 g $CaCO_3$ kg^{-1}), homogenized, air-dried soil (Table 1) in four consecutive layers as described by Hütsch and Schubert (2018). Fertilizer application followed Selzer and Schubert (2021) in both years: The top 40 kg of soil (equaling approximately 0–30 cm) were fertilized with 40 g compound fertilizer (Nitrophoska spezial Blau-Dünger) and micronutrients.

An overview of the 10 different treatments (*n* = 7) and cover crop plant densities is given in Table 2. Sowing densities were 20% higher than the aspired plant densities. One week after germination, plant density in the containers was adjusted to the values shown in Table 2. Plant densities of sunflowers and the mixture were adjusted in 2021. The plant density of sunflower was increased to 80 plants m^{-2} (Wendling et al., 2016), and the proportions of the individual cover crops in the mixture were adjusted to 14.3% of their respective plant densities in monoculture (Table 2). Two control treatments were included in the study, (1) a bare fallow and (2) a 'dummy' with non-transpiring, artificial plants (Figure S1). The height and leaf area index (LAI) of these artificial plants was adjusted according to the overall average height and LAI of the cover crops on a weekly basis.

2.1.1 | Meteorological conditions

Sensors were installed in radiation shields 161 cm above the ground (75 cm above the soil surface in the containers) and connected to data loggers (DK 320 HumiLog Plus, Driesen +Kern GmbH) which recorded temperature and relative humidity in 1 min intervals. Wind speed was measured using a cup anemometer (WSW G0010, F&C GmbH) linked to a data logger (DK312 MultiLog, Driesen +Kern GmbH) at a height of 350 cm above the ground (270 cm above the soil surface in containers).

The main water fluxes in the container experiment are depicted in Figure 1. The main water input consists of precipitation in the form of rainfall. In 2020, precipitation was quantified with a rain gauge which was checked twice a week. Rain gauge data were compared to hourly precipitation recorded with a tipping bucket at the nearby experimental station 'Weilburger Grenze' (50°36′6.12″N, 8°39′12.96″E). Since data from the rain gauge were comparable to those of the rain gauge, the hourly precipitation recordings from Weilburger Grenze were used in this study. Missing data were supplemented with data from the weather station in Giessen-Wettenberg (50°37′5.04″N, 8°39′38.04″E) of the German meteorological service (DWD). In October 2021, maximum wind speed data were neither recorded at Weilburger Grenze nor in Giessen-Wettenberg. Consequently, data for this parameter are missing from the results.

The temperature sum was calculated as growing degree days (GDD) based on Equation 1.

$$GDD = \frac{T_{max} - T_{min}}{2} - T_{base}. \tag{1}$$

TABLE 1 Comparison of container experiments in 2020 and 2021 with respect to cultivation practices, irrigation, soil properties, length and meteorological conditions during vegetation periods.

	2020	2021
Cultivation		
Sowing	24 August	25 August
Intermediate harvest 1	16 September	17 September
Intermediate harvest 2	1 October	5 October
Intermediate harvest 3	29 October	27 October
Preparation of mulch layer	–	27 October
Final harvest	6 November	29 March 2022
Soil properties		
Sand (%)	44.3%	52.9%
Silt (%)	34.6%	28.2%
Clay (%)	21.2%	19.9%
pH_{CaCl2}	5.4	5.6
pH_{CaCl2} (limed)	7.5	7.4
Vegetation period (d)	74	63
Precipitation (mm)	88	35
T_{mean} (°C)	13.3	13.1
GDD[a] (°C)	666	586
Irrigation	50% WHC	45% WHC

[a] GDD (growing degree days) = $\frac{T_{max} - T_{min}}{2} - T_{base}$, with T_{base} = 5°C (DWD, 2020).

Abbreviation: WHC, water-holding capacity.

with T_{max} = daily maximum temperature in °C, T_{min} = daily minimum temperature in °C, and T_{base} = base temperature in °C which was set at 5°C (DWD, 2020).

2.1.2 | Biomass production

Plant height and LAI (ACCUPAR LP-80 PAR/LAI Ceptometer, METER Group) were determined weekly throughout the vegetation period as the mean of four and three measurements per container, respectively. The length of the LAI sensor exceeded the width of the containers. Therefore, measured values were multiplied with a factor of 2.14 which was determined by calibration measurements (n = 10 for seven different lengths).

Three intermediate harvests were performed to assess above-ground biomass production (Table 1). On those dates, one container of each cover crop treatment was harvested by cutting the plants 1 cm above the ground. Fresh weight was determined gravimetrically.

In 2020, the vegetation period was terminated following the first frost event 74 days after sowing (DAS) from which sunflower and buckwheat plants did not recover (Selzer & Schubert, 2021). Cover crop fresh and dry weights (drying at 105°C) were determined gravimetrically. In 2021, after the first frost event 63 DAS, shoot fresh weight was determined gravimetrically before the biomass of frost-sensitive cover crops was cut into 3–5 cm pieces and placed back on top of the soil as a mulch layer. The fresh weight to dry weight ratio of the third intermediate harvest, which took place on the same day as the preparation of the mulch layer (Table 1), was used to determine biomass dry weight after the first frost (Equation 2).

$$\mathrm{DW} = \mathrm{FW} \bullet \frac{\mathrm{DW}_{\mathrm{IH3}}}{\mathrm{FW}_{\mathrm{IH3}}} \tag{2}$$

with DW = dry weight in kg m^{-2}, FW = fresh weight in kg m^{-2}, DW_{IH3} = dry weight at third intermediate harvest in kg m^{-2}, FW_{IH3} = fresh weight at third intermediate harvest in kg m^{-2}.

TABLE 2 Treatments and plant densities

Treatment	Plant density (plants m^{-2})
Bare fallow	–
Dummy	93
Sinapis alba L. cv. Gisilba	270
Raphanus sativus L. var. oleiformis Pers. cv. Bento	252
Lupinus albus L. cv. Feodora	70
Phacelia tanacetifolia Benth. cv. Amerigo	525
Fagopyrum esculentum Moench cv. Hainalka	315
Lolium perenne L. cv. Marava	1050
Helianthus annuus L. cv. SY Vivacio	12 (80)
Mix	9% (14%) white mustard – 16 (39) 9% (14%) oilseed radish – 15 (36) 20% (14%) white lupin – 14 (10) 9% (14%) phacelia – 32 (75) 9% (14%) buckwheat – 19 (45) 9% (14%) ryegrass – 63 (150) 33% (14%) sunflower – 4 (11)

Note: Mix: Plant densities of the individual species are given as the percentage of their respective plant density in pure stands and as a number of plants per square meter. Changes for the cultivation period 2021 in comparison to 2020 are given in parentheses.

The winter-hardy cover crop ryegrass was not mulched. Therefore, the fresh weight of ryegrass was only determined for one container which was harvested for the third intermediate harvest. The experiment was terminated at 216 DAS on 29 March 2022 (Table 1). On that date, the fresh weight of ryegrass and the cover crop residues was determined.

2.1.3 | Plant water dynamics

Two of the water losses by plants depicted in Figure 1 consist of evaporation (E) and transpiration (T). Evapotranspiration (ET) is defined as the sum of E and T. ET was calculated for each container using Equation 3 under the assumption that 1 L H_2O = 1 kg:

$$\mathrm{ET}_{\mathrm{ij}} = \left(\mathrm{C}_{\mathrm{i}} - \mathrm{L}_{\mathrm{hi}} + P_{ij} + I_{ij} - FW_{CCj} - C_j\right) \bullet 6.25 \tag{3}$$

With ET_{ij} = evapotranspiration between time i and time j in L m^{-2}, C_i = weight of container at time i in kg, L_{hi} = leachate accumulation between time h and time i, P = precipitation between time i and time j in L container^{-1}, I = irrigation between time i and time j in L container^{-1}, FW_{CC} = cover crop shoot fresh weight in kg container^{-1} and C_j = weight of container at time j in kg. The operational procedure made it necessary to determine the weight of the containers (C_i) before releasing the leachate from the drainage layer. Therefore, leachate accumulation until time point i (L_{hi}) was quantified and subtracted from C_i to determine the actual weight of the containers without leachate. Since the containers had a surface area of 0.16 m^2, the results were multiplied with the factor 6.25 to get ET losses in L m^{-2}. FW_{CC} was obtained from the different intermediate harvests.

Relevant water gains by plants, that is the occurrence of occult precipitation (Figure 1) was defined as periods with water inputs which could neither be explained by precipitation nor irrigation, that is $ET_{ij} > 0$.

Water use efficiency (WUE) is defined as the ratio of biomass accumulation to total water input to the system (Sinclair et al., 1984) (Equation 4).

$$\mathrm{WUE} = \frac{\mathrm{DW}}{(\mathrm{I} + \mathrm{P})} \tag{4}$$

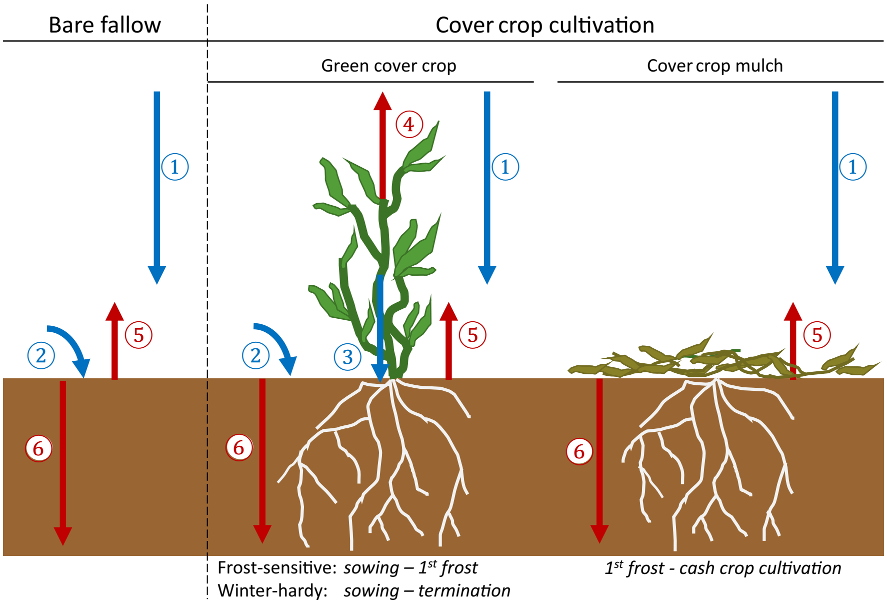

FIGURE 1 Water fluxes in the cover crop experiment. Water gains (blue): 1 = precipitation, 2 = irrigation, 3 = occult precipitation. Water losses (red): 4 = transpiration, 5 = evaporation, 6 = leaching.

with *WUE* = water use efficiency in kg L^{-1}, *DW* = shoot dry weight in kg m^{-2}, *I* = irrigation in L m^{-2} and *P* = precipitation in L m^{-2}.

2.1.4 | Soil water dynamics

Water gains

Water inputs by precipitation were recorded with a tipping bucket. Water inputs by irrigation (Figure 1) were recorded for each container. Cover crops were irrigated with deionized water twice a week to keep soil moisture at 50% WHC in 2020. Since we suspected luxury water consumption that year, we decided to reduce soil moisture to 45% WHC in 2021.

Water losses

The drainage layer at the bottom of the containers (Selzer & Schubert, 2021) allowed for the quantification and collection of leachate (Figure 1) throughout the vegetation period. The accumulated leachate was discharged through a valve and quantified gravimetrically after precipitation events on a weekly basis.

Water-holding capacity (WHC)

The soil water-holding capacity (WHC) of each container was calculated using Equation 5.

$$WHC_i = \frac{C_i - C_e - G - S - FW_{CCi}}{WC_{100\%}} \quad (5)$$

WHC_i = water-holding capacity at the time *i* in %, C_i = weight of container at the time *i* in kg, C_e = weight of the empty container in kg, *G* = weight of gravel in drainage layer in kg, *S* = weight of dry soil in kg, FW_{CC} = cover crop shoot fresh weight in kg $container^{-1}$ and $WC_{100\%}$ = water content of soil at 100% WHC in kg.

2.2 | Climate chamber experiments

2.2.1 | Experiment 1

A climate chamber experiment was carried out to identify under which climatic conditions occult precipitation occurs. The same plastic leaves that were used in the container experiments for the 'dummy' treatment were used to simulate a non-transpiring crop. Mitscherlich pots (Ø 30 cm) were filled with quartz sand. The plastic leaves were attached to 50 cm long stalks at a 45° angle and positioned in the quartz sand. The total height of the stalks and leaves was 73 cm and the LAI equalled 1.6 (uncorrected average LAI overall cover crop treatments in 2020). A ventilator (KE-60, 160 W, Kesser) was positioned 100 cm in front of the pot to regulate wind speed. Humidity in the climate chamber was set to 95% while a combination of various temperatures (5, 10, 15 and 20°C) and wind speeds (0.6 and 1.4 m s^{-1}) was tested in separate runs. The pots were weighed 0, 2, 4, 6 and 8 h after the start of each run to quantify occult precipitation. Each combination of meteorological conditions was repeated three times.

2.2.2 | Experiment 2

The same setup, wind speeds (0.6 and 1.4 m s^{-1}) and relative humidity (95%) as in Experiment 1 were used for Experiment 2. However, the temperature was not held constant over the weighing period. Creating more realistic conditions for fog formation, we simulated a temperature drop from 20 to 5°C while the other influencing factors were kept constant. The pots were weighed 0, 10, 20, 30, 60 and 120 min after the start of the temperature drop to quantify occult precipitation.

2.3 | Statistical analysis

Biomass and water fluxes of the different treatments were compared with a one-way analysis of variance (ANOVA) followed by a post hoc FDR test for each year. A White-adjusted ANOVA according to White (1980) and Long and Ervin (2000) was used for heteroscedastic data. A Grubb test was performed to identify outliers. This was relevant for WHC and leachate accumulation of white mustard on 22 February, 25 February and 1 March 2022. For these dates, only three of the four replicates were included in the results shown below. Where applicable, results from the two consecutive years were compared using a two-sided Student's *t*-test. Although the experimental setup was the same in both years, differences in water supply, the duration of the vegetation period and meteorological differences need to be considered when interpreting the results. The significance levels of all tests were chosen at $p < .05$. All tests were performed with RStudio (R version 4.1.0). The figures depict the means ± standard error (SE) which was calculated using Microsoft Office Excel (2019).

3 | RESULTS

3.1 | Meteorological conditions

In 2020, the average temperature during the 74-day vegetation period was 13.3°C with a maximum of 33.4°C 22 DAS and a minimum of −2.5°C (73 DAS) (Figure 2a). The average temperature during the vegetation period in 2021 was 13.1°C with a maximum of 30.4°C (12 DAS) and a minimum of −2.0°C (61 DAS) (Figure 2d). At the time of the first frost event, after which cover crops were either harvested (2020) or mulched (2021), a temperature sum of 666 and 586 growing degree days (GDD) was reached in 2020 and 2021, respectively.

Mean humidity during the first 35 days was <80% in 2020 (Figure 2b). Except for September, relative humidity was comparable in 2020 and 2021. Due to the absence of rain between 4 September and 22 September 2020, relative humidity was comparably low. From 28 September (35 DAS) onwards, mean relative humidity exceeded 80% and reached maximum values of 100% every day until harvest (74 DAS). In 2021, the mean humidity in September was higher than in 2020 (Figure 2b,e) due to more precipitation events. Wind speed reached maximum values of 4 m s^{-1} on several occasions, while the overall mean wind speed was 1.4 m s^{-1} in 2020 and 1.3 in 2021 (Figure 2c,f).

3.2 | Biomass production

White mustard was the cover crop with the highest shoot biomass in both years with ≥1 kg DW m^{-2} (Figure 3). Oilseed radish, phacelia, buckwheat and the mix of different cover crops also showed a quick development, good soil cover (Table S1) and high biomass production (Figure 3). Adjusting the plant density of sunflower in 2021 led to a significant increase in shoot dry weight in comparison to 2020, while white lupin and phacelia produced >20% less biomass in 2021 than in 2020 (Figure 3) due to differences in water supply, temperature sum and length of the vegetation period.

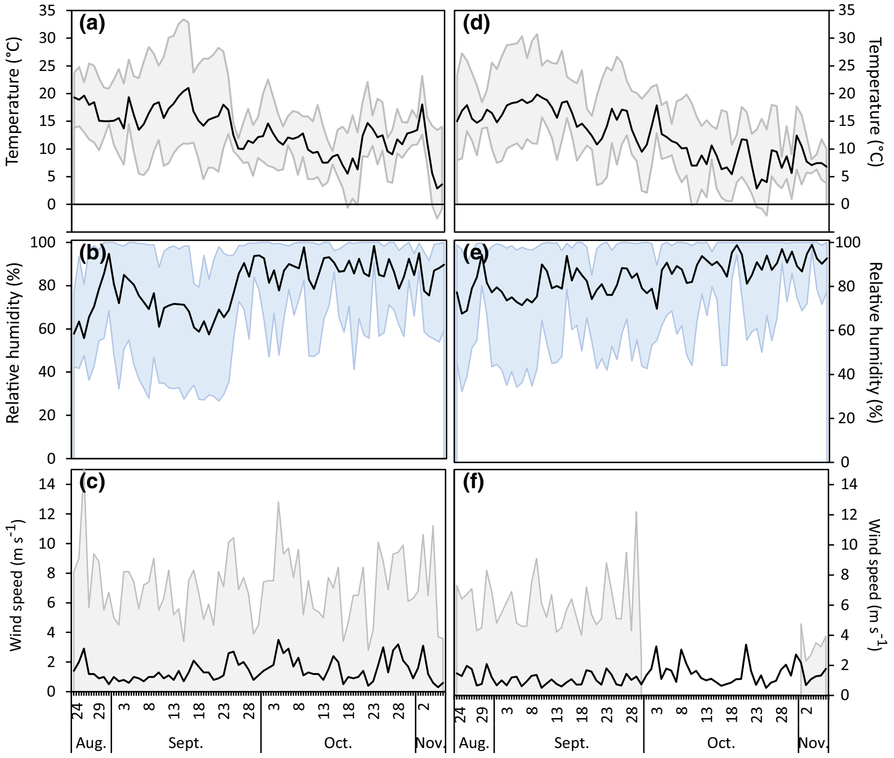

FIGURE 2 Meteorological conditions during the cover crop vegetation periods in 2020 (a–c) and 2021 (d–f). Depicted are (1) mean daily temperature (a + d, black solid line) and range between maximum and minimum daily temperature (grey area), (2) mean relative humidity (b + e, black solid line) and range between maximum and minimum daily humidity (grey area), and (3) mean daily wind speed (c + f, black solid line) and range between maximum and minimum daily wind speed (grey area).

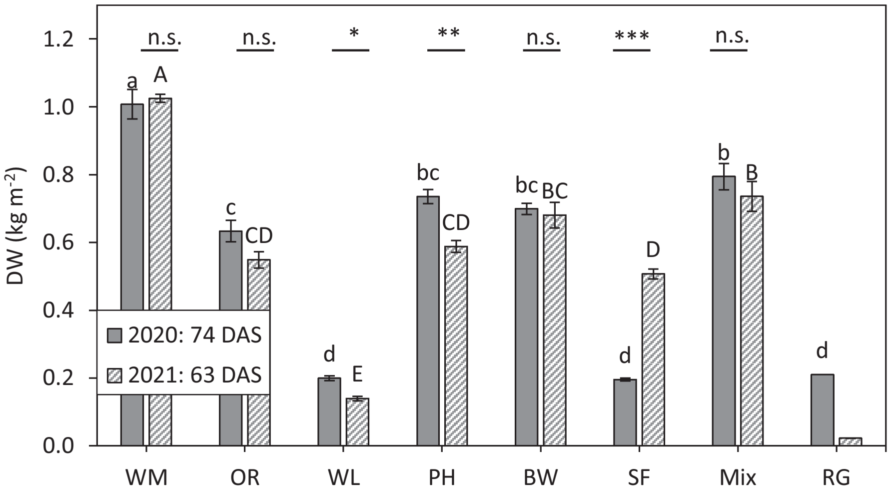

FIGURE 3 Shoot dry weight (DW) of various cover crops at the time of the first frost event 74 and 63 days after sowing (DAS) in 2020 and 2021, respectively. (BW, buckwheat; OR, oilseed radish; PH, phacelia; RG, ryegrass; SF, sunflower; WL, white lupin; WM, white mustard). One-way ANOVA and comparison of means adjusted according to FDR. Different letters indicate significant differences ($p<.05$), whereas small and capital letters indicate differences between cover crop species in 2020 and 2021, respectively. DW of the individual cover crops between the two consecutive years was compared using a two-sided Student's *t*-test (n.s., not significant; $^{*}p<.05$, $^{**}p<.01$, $^{***}p<.001$). Mean values ($n=4$, 2021: $n_{RG}=1$) ± SE.

3.3 | Plant water dynamics

3.3.1 | Water gains

Figures 4 and 5 depict plant water dynamics in the form of water inputs (irrigation and precipitation) and water losses (ET) for 2020 and 2021, respectively. Total precipitation during the vegetation period amounted to 88 mm in 2020 (Figure 4) and 35 mm in 2021 (Figure 5). Precipitation events were higher and more frequent in 2020 than in 2021. However, during the main growth period of cover crops in September 2020 (8–37 DAS), no precipitation occurred over a 20-day period (Figure 4). Accordingly, irrigation with up to 96 mm (white mustard) was necessary to keep soil moisture at 50% WHC (Figure 4). In both years, total precipitation in September was far below the long-term (1991–2020) average of 50 mm in Giessen (calculated based on data from the DWD) with 16 and 12 mm in 2020 and 2021, respectively. Precipitation in October 2020 (38–68 DAS) was within the range of the long-term average of 50 mm. However, October 2021 (37–67 DAS) was unusually dry with 68% less rainfall than in an average year.

The amount of irrigation in each treatment reflects the water losses through plant water use (transpiration), evaporation and leaching. Irrigation was applied to keep soil moisture at 50% and 45% WHC in 2020 and 2021, respectively. Accordingly, more irrigation water was needed in 2020 than in 2021, with the exception of sunflowers which had a higher irrigation requirement in 2021 due to the adjusted plant density (Table 2). Irrigation necessity was directly linked to biomass production. White mustard, the cover crop with the highest biomass in 2020 (Figure 3) was also among the cover crops with the highest the total irrigation necessity (184 mm, Figure 4). For phacelia, water supply by irrigation (176 mm, Figure 4) was similarly high in 2020 although biomass production was significantly lower than for white mustard (Figure 3). Cover crops with low biomass production (white lupin, ryegrass and sunflower) needed significantly less irrigation water (Figure 4). For example, total irrigation necessity of ryegrass was 80% lower than that of white mustard in 2020 (Figure 4). Similarly, differences in total irrigation were reflective of differences in biomass production in 2021 (Figures 3 and 5). For most of the vegetation period, the bare fallow and dummy did not require any irrigation to keep soil moisture at 50% and 45% WHC in 2020 and 2021, respectively (Figures 4 and 5).

The occurrence of occult precipitation was defined as periods in which ET > 0. This condition was neither met in 2020 (Figure 4) nor during the vegetation period 2021 (Figure 5) in any of the treatments. No water inputs via occult precipitation were quantifiable.

3.3.2 | Water losses

The crops with the highest biomass production, namely white mustard, oilseed radish, phacelia and the mixture of seven cover crops showed the highest ET losses in both years (Figures 4 and 5). The highest water losses by buckwheat and white mustard coincided with the beginning of flowering (both 31 DAS) in 2020 (Figure 4) while in 2021, white mustard lost most of its water after flowering began.

Although artificial plants provided a shading effect, there were no significant differences in the irrigation necessity or evaporative water losses between the two control treatments bare fallow and dummy (Figures 4 and 5). Total ET was significantly lower in those treatments compared to the cover crop treatments in both years (Figure 6).

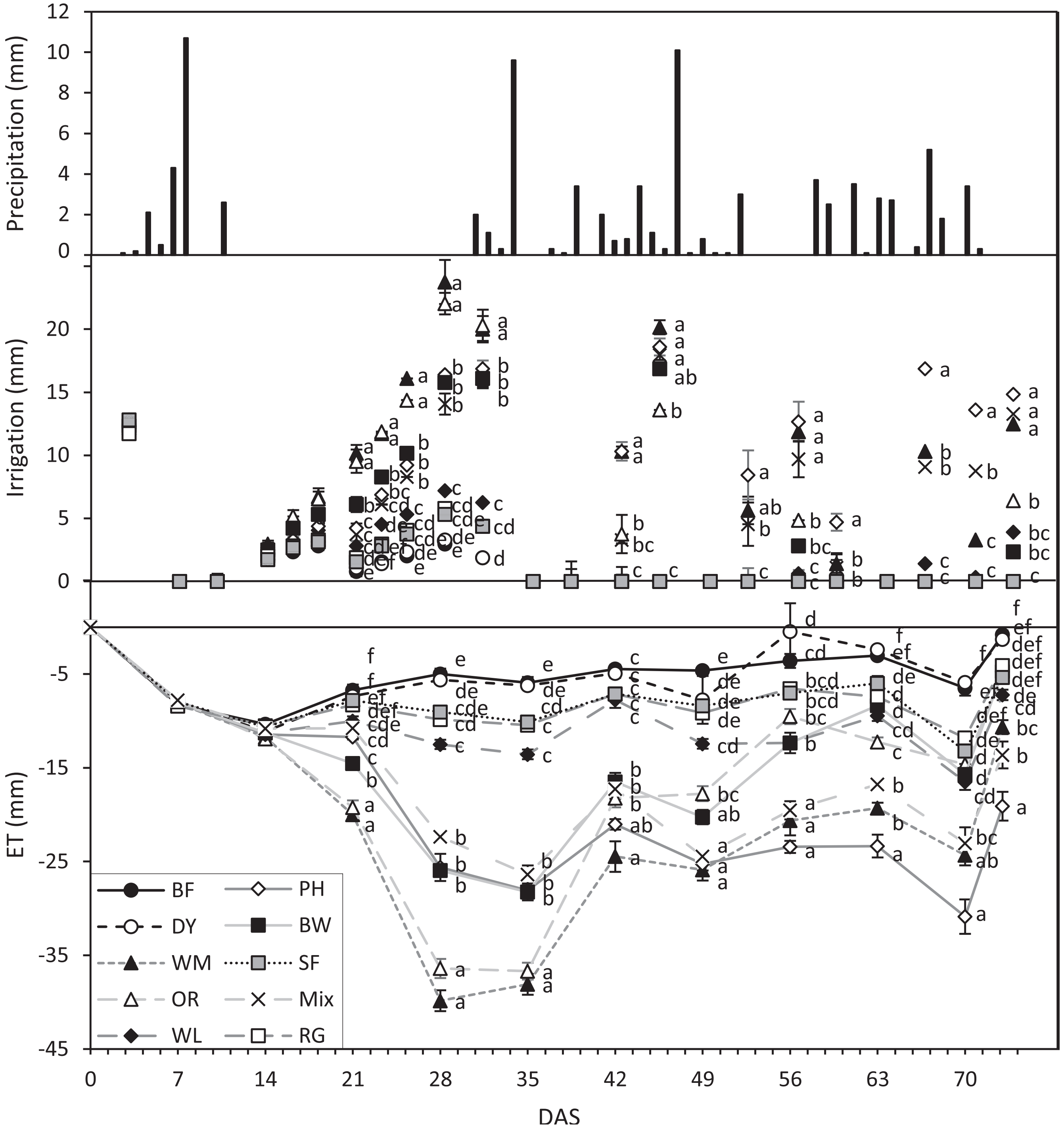

FIGURE 4 Water gains (precipitation and irrigation) and weekly water losses (ET) in 2020 until 74 days after sowing (DAS) (BF, bare fallow; BW, buckwheat; DY, dummy; OR, oilseed radish; PH, phacelia; RG, ryegrass; SF, sunflower; WL, white lupin; WM, white mustard). One-way ANOVA and comparison of means adjusted according to FDR. Different superscript letters indicate significant differences ($p < .05$) between treatments for that date. Mean values ($n = 4$) ± SE.

Total ET was representative of differences in shoot biomass production (Figures 3 and 6). With >256 mm white mustard and phacelia showed significantly higher ET than the other single and mixed cover crop treatments in 2020 (Figure 6). ET losses by cover crops were lowest for ryegrass and sunflower in that year (Figure 6), which were also among the cover crops with the lowest biomass production (Figure 3). Similar results were found in 2021. However, due to different meteorological conditions, management and a shorter growth period before the first frost event, cumulative ET in 2021 was on average 36% lower than in 2020. This difference was statistically significant for all cover crops with the exception of sunflowers (Figure 6). This can be attributed to the adjusted plant density of sunflowers in 2021 compared to 2020 (Table 2).

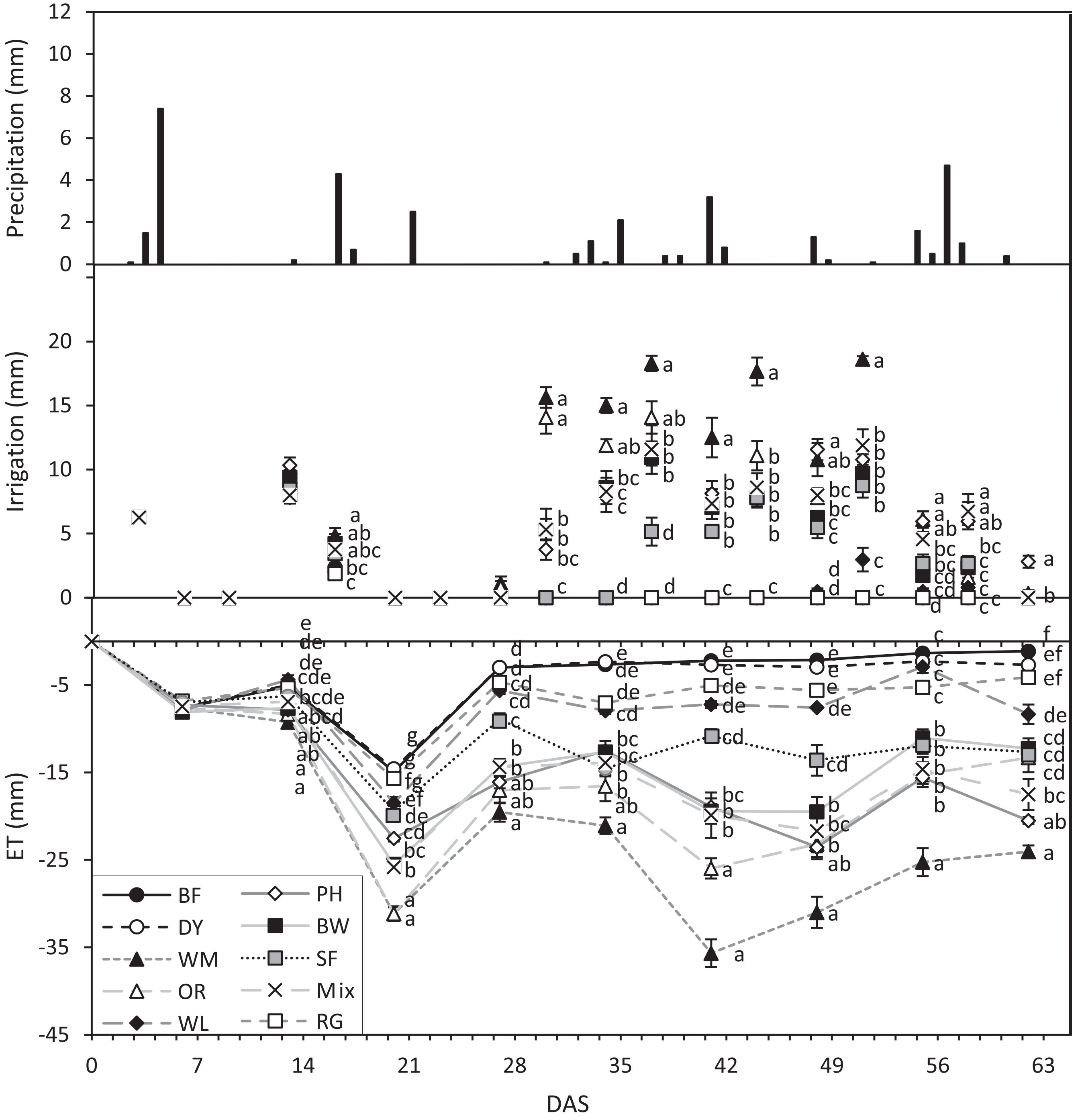

FIGURE 5 Water gains (precipitation and irrigation) and water losses (ET) in 2021 until 63 days after sowing (DAS) (BF, bare fallow; DY, dummy; WM, white mustard; OR, oilseed radish; WL, white lupin; PH, phacelia; BW, buckwheat; RG, ryegrass; SF, sunflower). One-way ANOVA and comparison of means adjusted according to FDR. Different superscript letters indicate significant differences ($p < .05$) between treatments for that date. Mean values ($n = 4$) ± SE.

Water losses in the form of leaching did not occur in the 63-day vegetation period in 2021 and leachate accumulation was only evident in three out of 40 containers in 2020 which could be explained by the preferential flow of irrigation water along the rim of the containers.

Water use efficiency (WUE) was defined as the ratio of shoot biomass production to total available water (Equation 4). Of the single-species treatments, white mustard and buckwheat showed the highest WUE followed by oilseed radish and phacelia in both years. WUEs of white lupin, ryegrass and sunflower, the cover crops with the lowest shoot biomass in 2020 (Figure 3), were <1.5 g DW L^{-1} in that year (Figure 7). The mix of various cover crops used the available water equally well as the most efficient single cover crops in both years. With an average increase of 55%, the WUE of

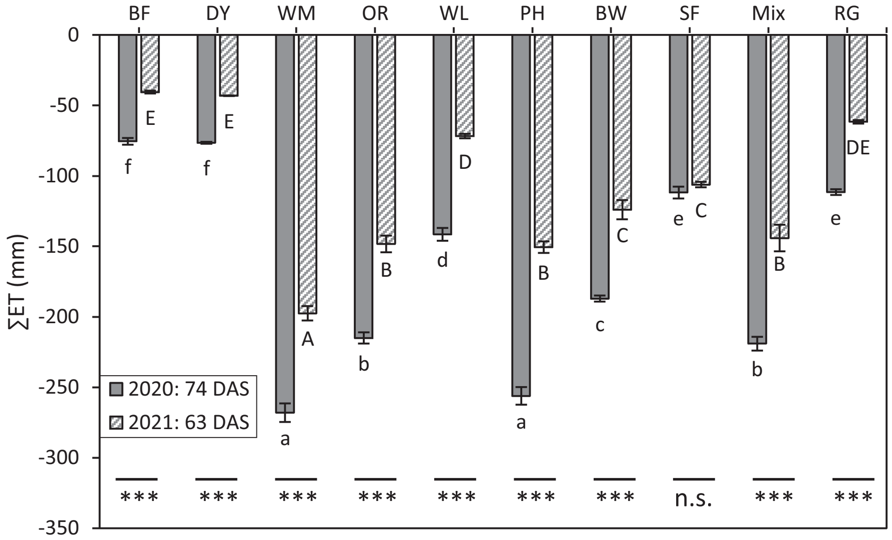

FIGURE 6 Cumulative evapotranspiration (ET) during the vegetation period of various cover crops (BW, buckwheat; OR, oilseed radish; PH, phacelia; RG, ryegrass; SF, sunflower; WL, white lupin; WM, white mustard) in 2020 and 2021 compared to two control treatments (BF, bare fallow; DY, dummy). One-way ANOVA and comparison of means adjusted according to FDR. Different letters indicate significant differences ($p < .05$), whereas small and capital letters indicate differences between cover crop species in 2020 and 2021, respectively. ET of the individual cover crops between the two consecutive years was compared using a two-sided Student's *t*-test (n.s., not significant; $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$). Mean values ($n = 4$) ± SE.

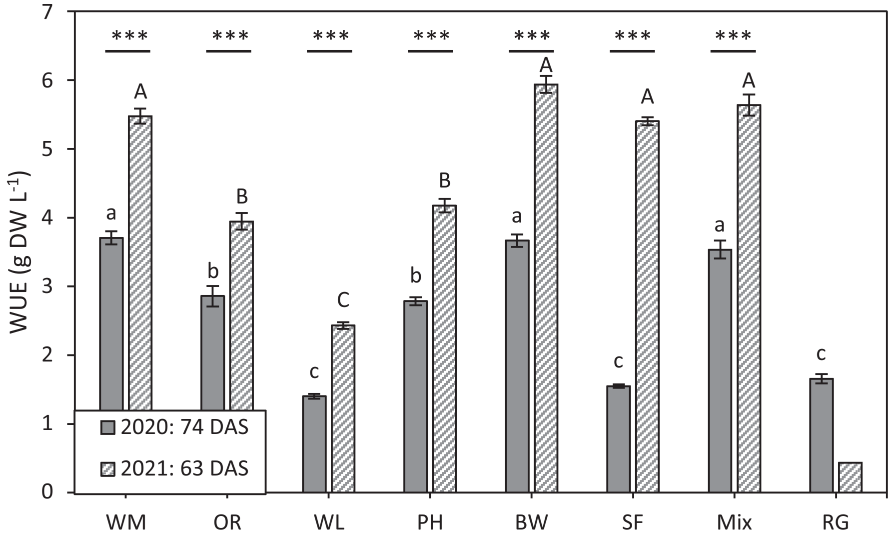

FIGURE 7 Water use efficiency (WUE) of various cover crops at the time of the first frost event 74 and 63 days after sowing (DAS) in 2020 and 2021, respectively (BW, buckwheat; OR, oilseed radish; PH, phacelia; RG, ryegrass; SF, sunflower; WL, white lupin; WM, white mustard). One-way ANOVA and comparison of means adjusted according to FDR. Different letters indicate significant differences ($p < .05$) where small and capital letters indicate differences between cover crop species in 2020 and 2021, respectively. WUE of the individual cover crops between the two consecutive years was compared using a two-sided Student's *t*-test (n.s., not significant; $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$). Mean values ($n = 4$, 2021: $n_{RG} = 1$) ± SE.

frost-sensitive cover crops in 2021 was significantly higher than in 2020. The increased WUE was due to reduced water inputs while biomass production only declined marginally for some of the crops (Figure 3). The adjustment of plant densities for sunflowers increased WUE by 249% in 2021. With 5.4 g DW L^{-1}, it had one of the highest WUEs and did not differ from white mustard, buckwheat or the mixture in that year (Figure 7).

3.4 | Soil water dynamics

The water gains and losses shown above directly influenced soil water dynamics. Although the soil was kept moist throughout the vegetation period, WHC differed significantly between treatments at the time of the first frost event. With >73% and >58% WHC in 2020 and 2021, respectively, soil moisture in the two control

TABLE 3 Soil water-holding capacity (WHC) at the first frost event in 2020 (74 DAS) and 2021 (63 DAS) and at the termination of the experiment (216 DAS).

	WHC (%)		
	2020	2021	
	First frost	First frost	Termination
Control			
BF	73.4 ± 0.5 ^{a}	60.0 ± 0.4 ^{a}	91.3 ± 1.5 ^{a}
DY	73.8 ± 0.3 ^{a}	58.4 ± 0.2 ^{a}	92.3 ± 1.4 ^{a}
Frost-sensitive			
WM	42.7 ± 0.4 ^{d}	39.4 ± 0.4 ^{ef}	87.0 ± 1.1 ^{a}
OR	47.1 ± 0.8 ^{c}	43.3 ± 1.2 ^{bcd}	86.8 ± 1.4 ^{a}
WL	47.6 ± 0.6 ^{c}	44.8 ± 0.7 ^{bc}	92.4 ± 1.9 ^{a}
PH	41.4 ± 0.3 ^{d}	36.6 ± 0.4 ^{f}	85.6 ± 1.4 ^{a}
BW	48.8 ± 0.1 ^{c}	46.0 ± 0.4 ^{b}	88.1 ± 1.6 ^{a}
SF	56.8 ± 1.8 ^{b}	41.2 ± 0.6 ^{cde}	84.0 ± 1.7 ^{a}
Mix	42.6 ± 0.3 ^{d}	40.6 ± 0.7 ^{de}	89.1 ± 1.9 ^{a}
Winter-hardy			
RG	57.8 ± 0.7 ^{b}	46.8 ± 0.8 ^{b}	68.2 ± 1.5 ^{b}

Abbreviations: BF, bare fallow; BW, buckwheat; DY, dummy; OR, oilseed radish; PH, phacelia; RG, ryegrass; SF, sunflower; WL, white lupin; WM, white mustard.

Note: One-way ANOVA and comparison of means adjusted according to FDR. Different superscript letters in a column indicate significant differences ($p < .05$). Mean values ($n = 4$) ± SE.

treatments bare fallow and dummy was significantly higher than in the cover crop treatments (Table 3).

This difference in soil moisture between the different treatments at the end of the vegetation period 2021 on October 27 (first frost) was no longer evident at the termination of the experiment in March 2022 (Table 3). Soil moisture increased after the preparation of the mulch layer in the treatments with frost-sensitive cover crops. During winter, soil moisture was restored to levels comparable to the control treatments. Soil moisture even exceeded 100% WHC on several occasions leading to leaching (Figure 8). For the winter-hardy cover crop ryegrass, soil moisture also increased. However, since ryegrass was not mulched, soil water recharge was slower than in the other treatments leading to significantly lower leaching. In early spring, when temperatures rose to 23.5°C (28 March, 215 DAS), WHC in the ryegrass treatment declined sharply from 90.4% on March 18 (205 DAS) to 68.2% on March 29 (216 DAS) (Figure 8) resulting in significantly lower soil moisture than in the other treatments (Table 3).

4 | DISCUSSION

4.1 | Methodology

4.1.1 | Determination of water fluxes

Calculating ET based on measurements which were performed twice a week can only give rather rough estimates of the various water fluxes shown in Figure 1. It is possible, therefore, that minor events of occult precipitation of a few millilitres per container might have been overlooked by this approach. However, since we were only interested in quantifying those water inputs with a quantifiable and relevant contribution to the cover crops' and the succeeding crops' water supply, the approach is justified. The results clearly illustrate that more precise measurements would not have changed the overall conclusion that occult precipitation did not have a relevant influence on the water balance of the cover crops.

Soil water storage is determined by the complex interplay of soil physical and chemical properties (Basche et al., 2016). While the focus of our experiments was on the effect of cover crops on water fluxes during two individual growth seasons, it has been shown previously that cover crops can have long-term effects on soil physical, biological and chemical properties which in turn enhance soil water storage capacity (McDaniel et al., 2014; Poeplau & Don, 2015) by increasing soil porosity (Villamil et al., 2006), reducing soil bulk density (Steele et al., 2012), increasing soil hydraulic conductivity (Klik et al., 1998) and promoting aggregate stability (Sainju et al., 2003; Villamil et al., 2006). These processes can improve water infiltration leading to an increasingly fast soil water recharge (Mubvumba et al., 2021) while the formation of crusts as a consequence of heavy rainfall restricts infiltration in bare soil (Hardie & Almajmaie, 2019). These long-term effects should not be neglected when considering the overall effects of cover cropping on soil water dynamics.

4.1.2 | Water supply

Since ET was positively correlated with water supply in all treatments in 2020, when soil moisture was kept at 50% WHC, we suspected that the high cumulative ET of up to 268 mm by white mustard (Figure 6) was caused by luxury water consumption. Figures 6 and 7 support the assumption of luxury water consumption. Although biomass production of white mustard did not differ between 2020 and 2021 (Figure 3), the cumulative ET of white mustard was 26% lower when soil moisture was kept at 45% compared to 50% WHC (Figure 6). In addition, the reduction of water availability led to a significant increase in WUE (Figure 7).

In both years, keeping the soil moist is likely to have increased cumulative ET losses compared to field conditions without irrigation. Thus, the ET of cover crops grown in the field is likely to be lower than the values shown in Figure 6. In this study, keeping the soil moist was justified by the attempt to create conditions for maximum water inputs through occult precipitation.

4.2 | Can we save water with cover crops?

Relevant amounts of occult precipitation, that is water inputs which could neither be explained by rainfall nor irrigation (ET > 0) (Holwerda et al., 2010), did not occur in the container experiment although preferential meteorological conditions for occult precipitation occurred on several occasions during both vegetation periods

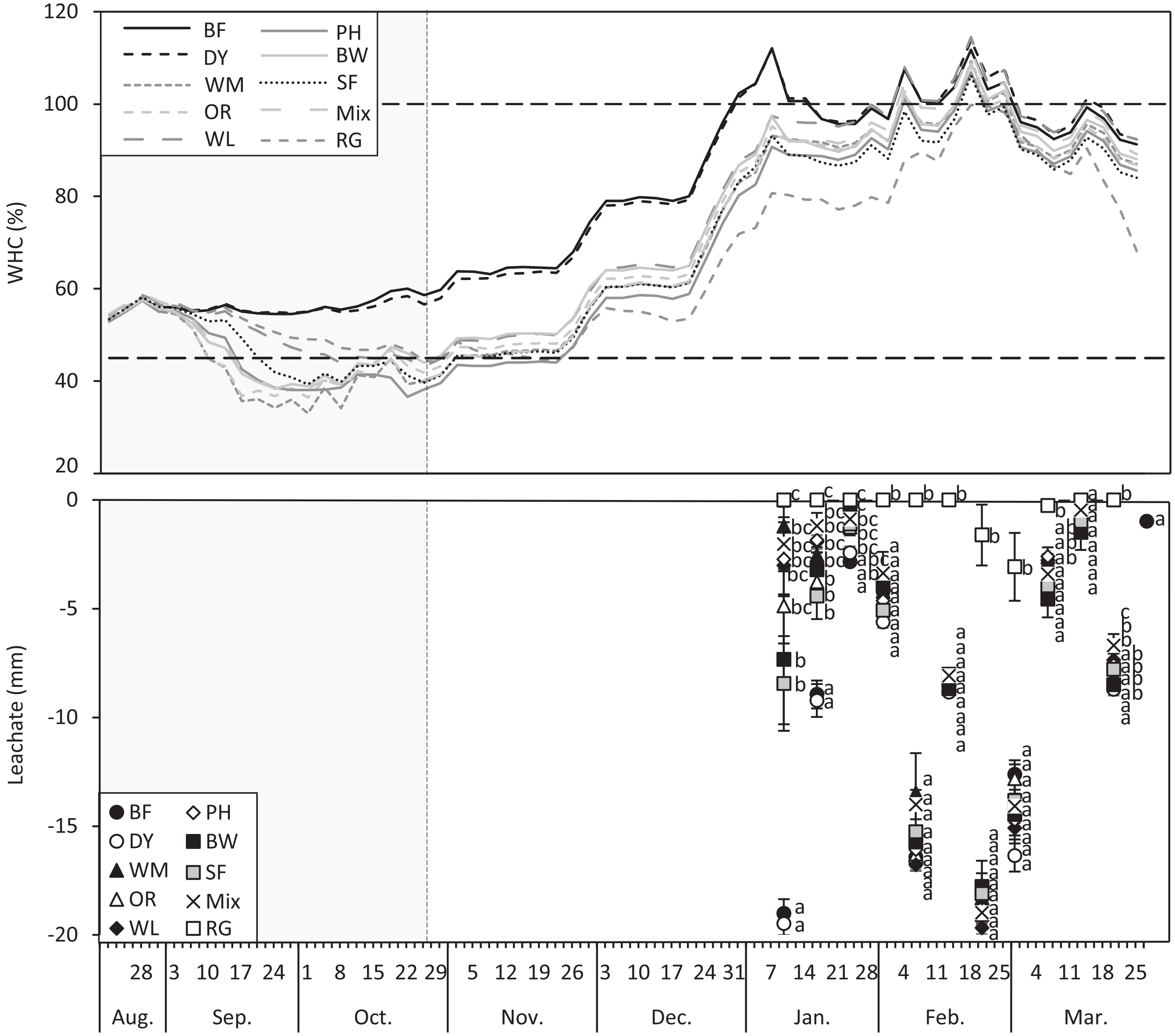

FIGURE 8 Time course of soil water-holding capacity (WHC) and leachate accumulation in the cover crop experiment in 2021. Preparation of mulch layer (dashed line) after first frost event 63 days after sowing (October 27) in frost-sensitive cover crop treatments (BW, buckwheat; OR, oilseed radish; PH, phacelia; SF, sunflower; WL, white lupin; WM, white mustard) with exception of the winter-hardy cover crop ryegrass (RG) in comparison to the control treatments bare fallow (BF) and a dummy (DY) with non-transpiring plants. One-way ANOVA and comparison of means adjusted according to FDR. WHC: mean values ($n = 4$). Leachate: different letters indicate significant differences ($p < .05$) between treatments for that date. Mean values ($n = 4$) ± SE.

(Figure 2). Instead, substantial water losses in the form of ET were evident (Figure 6) especially for cover crops with high biomass production and LAI (Figure 3, Table S1). Hence, the hypothesis that the occurrence of occult precipitation in cover crop treatments provides a water benefit in comparison to a bare fallow has to be rejected. At no point during the two vegetation periods were we able to quantify relevant water inputs through occult precipitation. This finding is supported by other studies which found that cover crops deplete soil water due to increased transpiration losses (McGuire et al., 1998; Mubvumba et al., 2021; Nielsen et al., 2015). Contradicting results have been presented in other studies which have found either an increase or no difference between the water content after cover crop cultivation and a bare fallow control (Alonso-Ayuso et al., 2014; Basche et al., 2016; Mubvumba et al., 2021; Rinnofner et al., 2008). However, in most of these studies, cover crop growth was terminated and the water content increased only after this termination (Alonso-Ayuso et al., 2014; Basche et al., 2016; Gentsch et al., 2022; Mubvumba et al., 2021). This clearly shows that increases in soil water cannot be attributed to an additional water input (occult precipitation) but to a reduction of water losses (transpiration and evaporation).

The aim of including a second control treatment, namely a dummy with non-transpiring plants, was to determine the net water input through occult precipitation without transpiration losses.

It was hypothesized that net water inputs would be higher in the dummy treatment than in the cover crop treatments. Although ET losses from the dummy were significantly lower than those of the cover crops, they did not differ from the bare fallow at any time during the vegetation periods (Figures 4 and 5) leading to the rejection of the second hypothesis. The results were supported by the climate chamber experiments in which the dummy did not harness any significant amounts of atmospheric moisture (Figure S2).

4.3 | Can we afford cover crops in times of increasing water scarcity?

Based on the results in Figure 8 and Table 3, we can accept the third hypothesis that soil moisture is recharged during the winter if cover crops are mulched while the winter-hardy cover crop ryegrass depletes soil water in spring due to an increase in transpiration. This may suggest that water is not a problem in cover crop cultivation when only frost-sensitive cover crops are grown. However, soil water recharge is not only dependent on the type of cover crop used but also depends on meteorological conditions and the management of the cover crops.

4.3.1 | Meteorological conditions

Sharma and Irmak (2019) pointed out that the net effect of cover cropping on soil water dynamics is highly dependent on timing and amount of precipitation. In 2021, the soil moisture of the bare fallow and dummy was higher than that of the cover crop treatments until the middle of January (Figure 8). Only due to exceptionally high rainfall in February with 72 mm compared to a long-term (1991–2020) average of 38 mm (calculated based on data from the DWD) soil water was restored and even exceeded 100% WHC. In areas with limited precipitation, cover crop cultivation can deplete soil water which adversely affects the yield of a succeeding crop (Islam et al., 2021). For semi-arid regions, it was shown that the soil water content in spring was 25%–35% lower under a green manure cover crop in comparison to a bare fallow resulting in a reduced yield of the subsequent wheat crop (Unger & Vigil, 1998). With increasingly irregular precipitation patterns (Trenberth, 2011), there is no guarantee that winter precipitation will restore soil water storage after cover crop cultivation not only in arid but also in (sub-) humid regions.

4.3.2 | Cover crop management

Alonso-Ayuso et al. (2018) have shown that a termination date is a meaningful tool for the regulation of water losses. In their study, a late termination (mid-April) of cover crops led to soil water depletion which increased pre-emptive competition with a succeeding crop. This was in agreement with results from this study where the winter-hardy cover crop reduced the soil water content in early spring (Figure 8). Similar results were found by Unger and Vigil (1998) who have shown that due to lower water availability, the yield of a succeeding grain crop decreased if cover crops were allowed to reach maturity in comparison to a cover crop which was desiccated. It is shown in this study that early termination of cover crop growth allows soil water to recharge during winter under favourable weather conditions (Figure 8). However, early termination can have negative effects on other ecosystem services provided by cover crops: Leachate volume was significantly higher in the mulched cover crop treatments in comparison to the winter-hardy ryegrass (Figure 8).

Not only the time of termination but also the management of cover crop residues directly affects soil water dynamics. One management option which was tested in this study is mulching. At termination, the soil water content in the mulched treatments was significantly higher than in the treatment with winter-hardy ryegrass. However, it did not differ from the water content in the bare fallow treatment (Table 3). Even though a mulch layer effectively increases soil water content due to the termination of transpiration losses and the significant reduction of evaporation in comparison to a bare fallow (Chalise et al., 2019), soil moisture in the cover crop treatments declined equally fast as in the bare fallow treatment in this study (Figure 8).

Possible reasons for this reduction of soil moisture in the mulched treatments are threefold: Firstly, decomposition processes during winter reduced cover crop biomass to ≤10% of its original fresh weight (Figure S3). Tolk et al. (1998) have shown that next to the evaporative demand of the atmosphere, the thickness of the residue determines the rate of evaporation. While the mulch effectively covered the soil in November 2021, it hardly provided a closed cover in February and March 2022 (Figure S4) when temperatures rose and evaporative water losses started to increase again. The decomposition rate is determined by (1) microbial activity which depends on temperature and soil pH, (2) the chemical composition of the organic matter and (3) water availability. Coppens et al. (2007) have shown that moisture limitation is even more important than N limitation for mulch decomposition. In this study, neither N availability nor soil moisture was limiting factors. The C:N ratio of the cover crops was ≤23 in 2020 (Selzer & Schubert, 2021) and after the preparation of the mulch layer soil moisture increased steadily in all treatments (Figure 8), providing good conditions for mineralization. The rapid decomposition of cover crop residues was also evident in a semi-arid environment where it reduced the positive effect of cover crops on soil physical properties (Blanco-Canqui et al., 2013) which are closely related to soil water dynamics.

Secondly, returning residue to the soil as a mulch has been shown to increase soil water retention in the upper 5 cm of soil due to an increased soil organic carbon content and a reduction of soil bulk density (Chalise et al., 2019). This improved water retention in the topsoil might have contributed to higher evaporation losses at the soil surface in comparison to the bare fallow treatment which has lower water retention at the soil surface.

Thirdly, the darker colour of the mulch in comparison to the bare soil surface could have increased the absorption of solar radiation (Massee & Cary, 1978) thereby promoting faster heating of the upper few centimetres of the soil, leading to higher water losses due to evaporation.

Thus, from a water budget viewpoint, cover cropping can only be afforded if cover crop growth is terminated early enough to minimize water losses through transpiration while simultaneously maximizing the other benefits cover crops provide to a cropping system. However, cover crop management is not the only determining factor. Water scarcity is already one of the main reasons for farmers to decide against the adaptation of cover crops in some regions in Germany (personal communication). Consequently, even with good management practices in place, cover crops can only be afforded in regions where winter precipitation is sufficient for soil water recharge after the depletion of soil water by cover crops in autumn.

AUTHOR CONTRIBUTIONS

Tabea Selzer: Conceptualization; data curation; writing – original draft preparation; writing – review and editing. **Sven Schubert:** Conceptualization; supervision; writing – review and editing. All authors have read and agreed to the published version of the manuscript.

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DATA AVAILABILITY STATEMWNT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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