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Weed suppressive ability of cover crops under water-limited conditions

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Abstract: The water demand for cover crops (CC) should be considered to achieve competitive crop stands for weed control also under unfavorable conditions. This study aims to estimate the weed suppressive ability of winter CC, as *Sinapis alba* L., *Phacelia tanacetifolia* Benth., *Vicia sativa* L. and *Avena strigosa* Schreb., under a water-limited regime. The water deficit tolerance of different CC was determined in a greenhouse experiment by measuring the maximum quantum efficiency of photosystem II. Moreover, soil moisture, CC, and weed establishment were measured in field experiments in Southwest-Germany during two contrasting growing seasons in 2016 and 2017. *A. strigosa* showed a higher water deficit tolerance than *S. alba* in the greenhouse. In the field, *A. strigosa* showed the highest weed cover reduction (98%) in the field, along with an increasing effect on the soil moisture compared to the untreated control. *S. alba* performed most sensitive to water deficit in the greenhouse but reached the significantly highest weed control efficacy (94%) during the dry field season in 2016. Even though the selected CC showed differing sensitivities to water deficit in the greenhouse, their weed suppression ability was independent of the water supply under field conditions.

Keywords: abiotic stress; catch crop; chlorophyll fluorescence; weed management; water balance

The increasing interest on cover crops (CCs) is caused by their associated benefits (Snapp et al. 2005) like weed suppression (Teasdale and Mohler 2000), nutrient recycling efficiency, soil erosion reduction (Snapp et al. 2005) and cash crop productivity (Abdin et al. 2000). However, CCs may change the water balance significantly (Ward et al. 2012). In water-limited regions, producers do not opt for integrating winter CCs between two cash crops, as CCs might decrease the restoration of soil water resources, which may lead to a lower soil water content for the following spring crop (Wortman et al. 2012).

If negative effects on the following cash crop are not expected, single CCs or cover crop (CC) mixtures are a suitable weed control measure during the fallow period from fall to spring. CCs suppress weeds during cultivation by competition for resources and by releasing biochemical compounds (Gfeller et al. 2018). To increase the weed control ability of CCs, an early CC establishment in fall, in combination with high biomass production and complete soil coverage, are targeted (Brennan and Smith 2005, Finney et al. 2016). To achieve appropriate CC stands, CCs need to be resilient to abiotic stresses, including water deficits, as the probability of extreme weather events seems to rise due to climate change (IPCC 2014).

This study aims to estimate the water demand of some commonly used winter CCs in Germany and their weed suppressive ability under moist and water-limited conditions. *Vicia sativa* L. (Fabaceae) has quite low habitat requirements and even increases water infiltration rates (Decker et al. 1994) but seem to respond sensitively to dry conditions (Tribouillois et al. 2016). *Phacelia tanacetifolia* Benth., which

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belongs to the family of Hydrophylaceae, requires higher water potentials for germination and prefers, as *V. sativa*, mild temperatures (below 30°C) for germination (Tribouillois et al. 2016). In comparison, *Raphanus sativus* var. *oleiformis* Pers. and *Sinapis alba* L., which belong to the family of Brassicaceae and *Avena strigosa* Schreb. (Poaceae) seem to be more tolerant to water deficits during germination (Tribouillois et al. 2016). This study evaluates how these CCs are affected by water deficit and if themselves contribute to lower soil moisture contents compared to the control without CCs. Thereby, the following questions were addressed: (i) Do *P. tancacetifolia*, *S. alba*, and *A. strigosa* show differing sensitivities to water deficit in greenhouse and field experiments; (ii) is the water stress tolerance of CCs determining their weed suppression ability, and (iii) is the soil moisture content from fall to winter affected by cover cropping.

MATERIAL AND METHODS

Greenhouse experiment: Experimental set-up. A greenhouse pot trial was conducted twice to assess the tolerance to water deficit of *S. alba*, *P. tanacetifolia*, and *A. strigosa*. A randomized complete block design with 4 repetitions per treatment was used. The greenhouse temperature was set to 20/14°C day/night at a 12 h photoperiod. To receive a unique set of plants, plants were pre-grown in vermiculite until the second leaf was unfolded. At this time, three seedlings of one species were transplanted to one plastic pot (7 × 7 × 8 cm), which was filled with 350 g of soil (60% sand, 28.7% silt, and 11.3% clay). One pot served as one repetition. After transplanting, plants were grown 7 days with full water supply. The trial consisted of 15 treatments of different periods without irrigation. The durations without irrigation ranged from 1 to 14 consecutive days without water supply. Whereby, e.g., treatment 2 and 14 were not irrigated for 2 and 14 days, respectively. A control, which was irrigated throughout the whole trial period, was included. Each pot of the respective treatment was irrigated with 30 mL of water until field capacity after reaching the first day of irrigation and every second day afterward.

Before the first time of irrigation, the maximum quantum efficiency of photosystem II (F_v/F_m) was determined with an Imaging PAM M-Series chlorophyll fluorometer (Heinz Walz GmbH, Effeltrich, Germany) to receive information on the physiological plant status at the end of the water-limited period. Before the measurements, plants were dark acclimated for 30 min. Afterward, the ground fluorescence (F_o) and the maximum fluorescence (F_m) were determined. The variable fluorescence (F_v) was calculated by subtracting F_o from F_m. The F_v/F_m value was calculated as:

$$F_v/F_m = (F_m - F_o)/F_m \tag{1}$$

The F_v/F_m value is a commonly used parameter to receive information on photosynthetic efficiency (Baker 2008). It can be used to quantify plant stress in plants of diverse origin (Rosenqvist and van Kooten 2003). In healthy conditions, the F_v/F_m value is ~ 0.8 (Björkman and Demmig 1987), while lower values indicate plant stress.

Field experiments: Experimental and meteorological conditions. Two field experiments were conducted in Southwest-Germany at the research station of the University of Hohenheim (48.74°N, 8.92°E, 475 m a.s.l.) near Renningen from August until December in 2016 and 2017. The soil at Experiments 1 and 2 in 2016 was classified as a silty clay (6% sand, 53% silt, and 41% clay). Soil texture of 6% sand, 65% silt and 29% clay was indicated at Experiment 1 in 2017. In 2017, the soil type at Experiment 2 was a silty loam (27% sand, 48% silt and 25% clay). The monthly weather details and the water balance are shown in Table 1. The daily water balance (D, mm) was calculated as:

$$D = P - ET_o \tag{2}$$

While P is the precipitation (mm) and ET_o the crop reference evapotranspiration (mm). ET_o was calcu-

Table 1. Mean temperature, total precipitation, water balance and total crop reference evapotranspiration (ET_o)

Year	Month	Temperature (C°)	Precipitation	ET_o	Water balance
			(mm)		
2016	July	18.1	64.8	115.7	−50.9
	August	17.8	29.3	107.9	−78.6
	September	16.4	50.6	76.7	−26.1
	October	8.1	53.3	26.9	26.4
	November	3.6	48.7	11.7	37.0
	total	12.8	246.7	338.9	−92.2
2017	July	18.1	109.9	109.9	0.0
	August	18.1	69.3	94.5	−25.2
	September	12.1	52.2	52.7	−0.5
	October	10.8	51.1	37.2	13.9
	November	4.2	63.0	11.9	51.1
	total	12.7	345.5	306.2	39.3

Table 2. Experimental set-up and conditions of the field trials

	2016		2017	
	Experiment 1	Experiment 2	Experiment 1	Experiment 2
Crop rotation	winter wheat-cover crop		winter wheat-cover crop	winter barley-cover crop
Cereal harvest date	08/08/2016		10/08/2017	05/08/17
Soil preparation (depth)	stubble cultivator + deep tillage (15 cm) + power harrow (6–8 cm)		stubble cultivator + deep tillage (15 cm) + power harrow (6–8 cm)	
Sowing date	19/08/2016		25/08/2017	
Sowing depth (cm)	2		2	
Soil texture	silty clay		silty clay loam	silty loam

lated using the ET_o calculator version 3.2 (FAO 2012). The soil textures, crop rotations, and field preparations for Experiments 1 and 2 are shown in Table 2.

Set-up and data acquisition of Experiment 1. Experiment 1 was conducted with 3 treatments and 8 replications within a randomized complete block design. In 2016 and 2017, *S. alba*, *P. tanacetifolia*, and *A. strigosa* (Deutsche Saatveredelung AG (DSV), Lippstadt, Germany) were sown in pure stands with seed densities of 25, 10 and 120 kg/ha, respectively within 30 m^2 plots. A control treatment without CCs was included. The weed flora was determined 7 weeks after sowing (WAS). CC and weed dry matter were measured after harvesting, washing, and drying 0.25 m^2 fresh material 7 WAS.

According to Rasmussen (1991), weed control efficacy (WCE) was calculated as:

$$\text{WCE (\%)} = 100 - wt/(0.01 \times wc) \tag{3}$$

Where: *wt* – weed dry matter (kg/ha) of the CC treatments; *wc* – weed dry matter (kg/ha) of the control without CCs.

Set-up and data acquisition of Experiment 2. *R. sativus*, *V. sativa*, *P. tanacetifolia*, and *A. strigosa* were sown, in 2016 and 2017, in 60 m^2 plots with seed densities of 25, 100, 10 and 120 kg/ha, respectively. Experiment 2 was set up as a randomized complete block design with four replications. Within the control treatment, no CC was sown. Soil moisture contents were measured within one tube per plot by a frequency domain reflectometry device called PR2 probe (Profile Probe; Delta-T Devices Ltd., Burwell, UK). The soil cover of CCs and weeds were estimated four times per plot with a metal frame, covering an area of 0.25 m^2, 7 WAS. The weed community was also determined 7 WAS.

Data analysis (field and greenhouse experiments). The software R (version 3.5.1, R Foundation for Statistical Computing, Vienna, Austria) was used for data analysis. The data were visually checked for normal distribution and homogeneity of variance. Based on the F_v/F_m values, dose-response curves were calculated with a three parametric log-logistic model and checked for fit with a lack-of-fit test (Ritz et al. 2015). To receive differences in the resilience to water deficit of the different CCs, the duration for a reduction of 50% in the F_v/F_m value (TE_{50}) was calculated. An analysis of variance (ANOVA) was performed for the TE_{50} and the ground truth field data collected for the field Experiments 1 and 2. Differences, of the treatment means, were obtained using a Tukey-*HSD* (honestly significant difference) test with $P \leq 0.05$.

RESULTS AND DISCUSSION

Within the greenhouse experiment, *S. alba* showed the highest sensitivity to water scarcity (Figure 1)

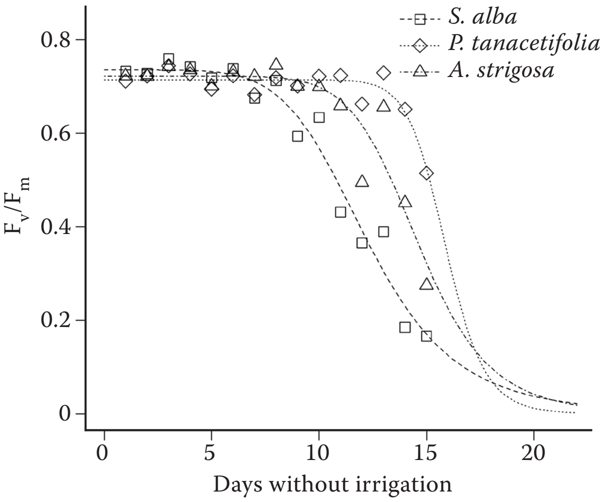

Figure 1. Dose-response curves of the maximum quantum efficiency of the photosystem II (F_v/F_m) response of *Sinapis alba* L., *Phacelia tanacetifolia* Benth. and *Avena strigosa* Schreb. to days without irrigation

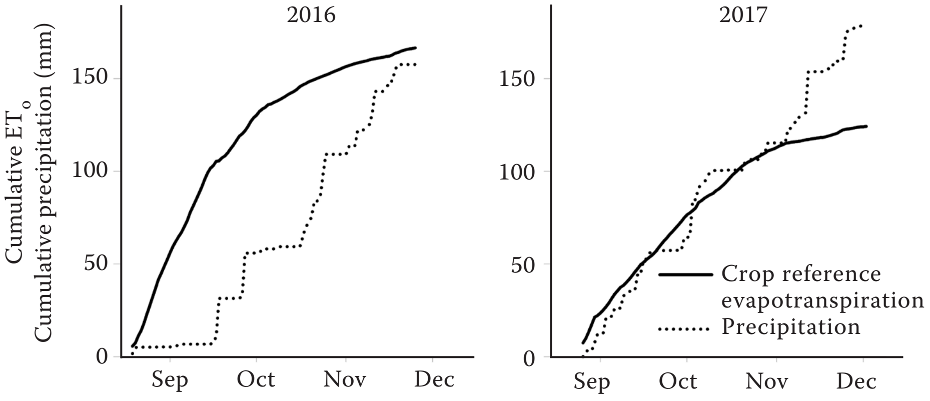

Figure 2. Cumulative reference crop evapotranspiration (ET_o) and precipitation from August until December 2016 and 2017

and reached TE_{50} already after 12.3 days without irrigation, whereas *A. strigosa* reached TE_{50} after 14.6 days. *P. tanacetifolia* showed the significantly highest tolerance to water deficit and exhibited a TE_{50} of 15.9 days without irrigation.

A similar weed community composition was noticed in the experimental field for both the experiments. In 2016, volunteer crops (Experiment 1 and 2: winter wheat) and annual broad-leaved weeds like *Capsella bursa-pastoris* M., *Chenopodium album* L., *Galium aparine* L. and *Lamium purpureum* L. dominated the weed community. In 2017 at Experiment 1, *C. album*, *G. aparine*, *Stellaria media* L. and volunteer crops (winter wheat) were dominating. *C. bursa-pastoris*, *L. purpureum*, *Matricaria* spp. and volunteer crops (winter barley) were predominant in the weed flora of Experiment 2 in 2017. The field sites showed a water equilibrium of −92.2 mm in 2016 (from July until November) and a water equilibrium in 2017 with 39.3 mm within the same months (Table 1). The amount of water, which was lost by ET_o in 2016, exceeded the amount of precipitation throughout the whole season (Figure 2). Due to the water deficit in 2016, the maximum amount of dry matter with 1002 kg/ha (*S. alba*) in Experiment 1 was almost 60% lower than the maximum amount of dry matter in 2017 (*S. alba*) (Figure 3).

Even though the highest sensitivity to water scarcity was measured for *S. alba* in the greenhouse, *S. alba* was unimpaired by water deficits in the field. This is consistent with literature where mustard is described as drought-tolerant (Brown et al. 2005, Tian et al. 2014). Bodner et al. (2007) found that *S. alba*, when used as a CC, shows high evapotranspiration losses compared to CCs like vetch and phacelia. However, according to their study, *S. alba* compensates for these water loss with a high biomass production,

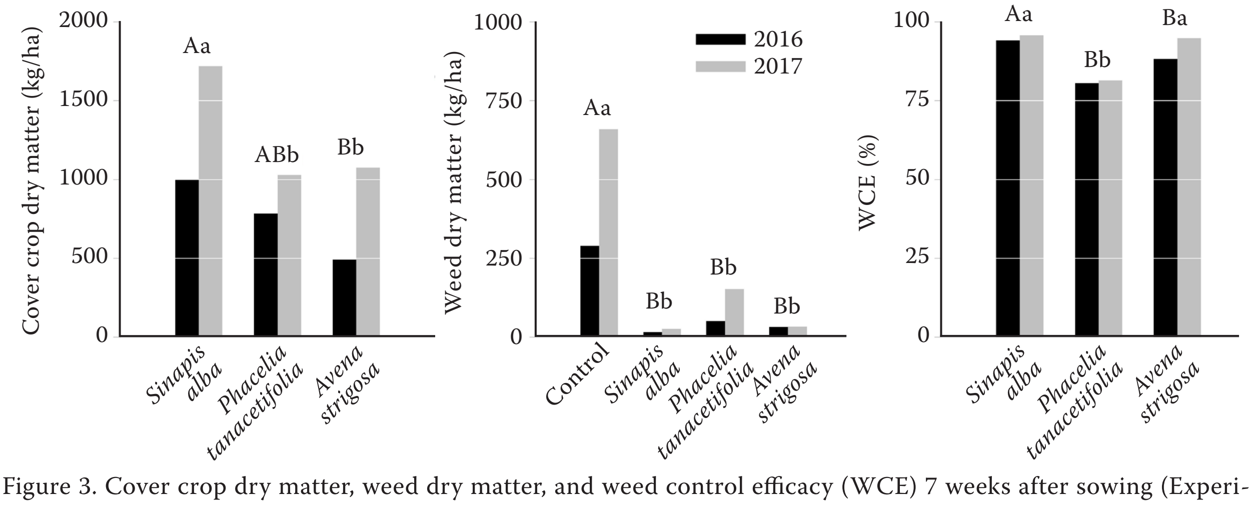

Figure 3. Cover crop dry matter, weed dry matter, and weed control efficacy (WCE) 7 weeks after sowing (Experiment 1). Capital letters within one graph show significant differences in 2016, according to the Tukey-*HSD* (honestly significant difference) test ($P \leq 0.05$). Small letters within one graph show significant differences in 2017, according to Tukey-*HSD* test ($P \leq 0.05$)

which increased the competition with weeds. In the field, *S. alba* showed the lowest weed dry matter and highest WCE with ~96% in both years (Experiment 1). This result agrees with other studies that also suggest *S. alba* as being suitable as an efficient weed control measure. Brust et al. (2014) and Kunz et al. (2016) showed a weed density reduction between 57–59% compared to the no-CC control. Björkman et al. (2015) showed a reduction of more than 50% in 9 of 10 study cases with weed biomass reductions by up to 99% by *S. alba* as compared to the untreated control. *A. strigosa* reached a similar WCE of 95% (Experiment 1 in 2017) and the highest reduction of weed coverage as compared to the control with 98% (Experiment 2 in 2017 (Figure 4)).

V. sativa was also able to significantly reduce the weed coverage as compared to the control in 2017. Nevertheless, following Baraibar et al. (2018), *V. sativa* showed a weaker weed suppression potential than the Brassicaceae or Poaceae species. Also, Nielsen et al. (2015) indicated that grasses are more competitive than legumes. Additionally, *V. sativa* is being expected to be more sensitive to drought during germination (Constantin et al. 2015). *P. tanacetifolia* showed the highest tolerance to water deficit in the greenhouse. While producing a similar amount of dry matter per unit area as *A. strigosa* (Experiment 1 in 2017), *P. tanacetifolia* demonstrated a significantly weaker WCE than *S. alba* and *A. strigosa.* Additionally, *P. tanacetifolia* exhibited a great level of coverage ability (62%) in 2016 and decreased weed coverage by 67%. However, it was only as efficient as *R. sativus*, with only 42% of soil coverage (Figure 4). In conclusion, CCs are attributed to an efficient weed suppression potential if they are strong resource competitors, show an early CC canopy development (Brennan and Smith 2005) and produce a certain biomass amount (Finney et al. 2016, Gfeller et al. 2018). However, biochemical weed suppression mechanisms of CCs, as attributed to, e.g., the family of Brassicaceae or Poaceae (Belz 2007), seem to contribute substantially to the weed suppression success. The weed suppressive effects of *A. strigosa* are reported to be considerably during cultivation and afterward (Brust and Gerhards 2012, Price et al. 2006, Schappert et al. 2019). *A. strigosa* showed a great weed suppression potential during the dry season, even though the dry matter production of *A. strigosa* was quite low. Plant stress, as, e.g., induced by water deficits, may enhance the allelopathic potential (Einhellig 1996), which might have contributed to efficient weed control by *A. strigosa* during the dry season in 2016.

Although allelopathy seems to contribute to weed control during CC cultivation, its effects on the subsequent cash crop should not be neglected. It is reported by Sturm and Gerhards (2016) that mulch of *R. sativus* is inhibiting crop germination and root length, which was attributed to the allelopathic potential of Brassicaceae. However, allelopathic compounds, like isothiocyanates emitted by *Brassica napus*, were described to disappear quickly as compared to the decomposition of the CC residue mulch layer, which functions as a physical barrier to weeds (Yenish et al. 1995, Petersen et al. 2001). This might explain why maize emergence was unaffected after growing

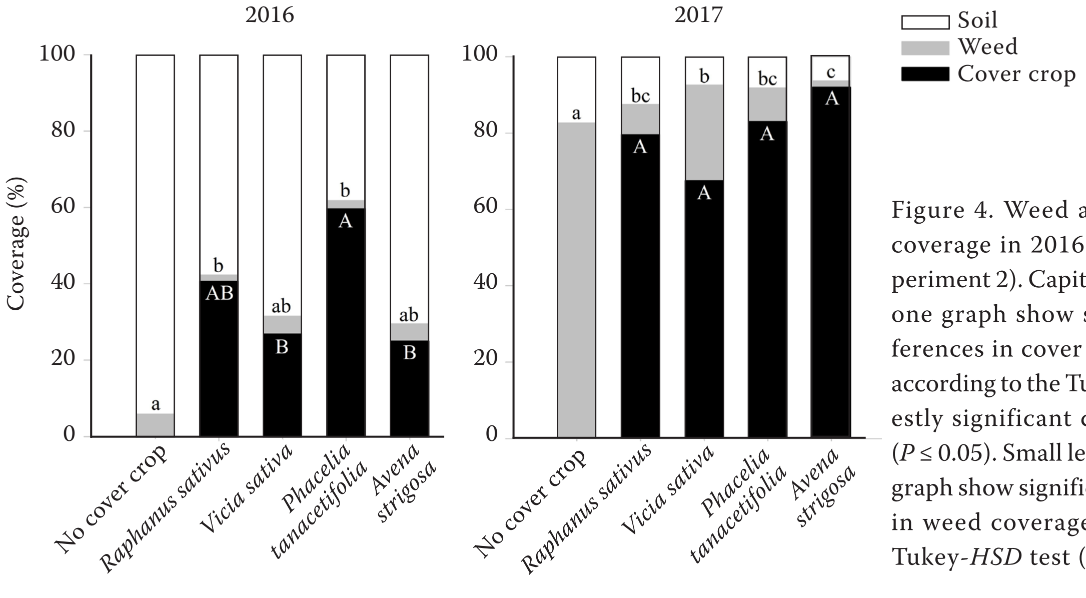

Figure 4. Weed and cover crop coverage in 2016 and 2017 (Experiment 2). Capital letters within one graph show significant differences in cover crop coverage, according to the Tukey-*HSD* (honestly significant difference) test ($P \leq 0.05$). Small letters within one graph show significant differences in weed coverage, according to Tukey-*HSD* test ($P \leq 0.05$)

winter cereals as CCs within a study from Dhima et al. (2006) and after growing Poaceae and Brassicaceae CCs within this study (data not shown). In contrast, *A. strigosa* is very popular in Brazil as a preceding crop to soybean. In this specific combination, *A. strigosa* was reported to increase crop yield as compared to other CC treatments and a winter fallow (Derpsch et al. 1986, Price et al. 2006).

In 2016, when CCs generally developed poorly, *V. sativa* and *A. strigosa* increased the soil moisture content compared to the *P. tanacetifolia*, *R. sativus* var. *oleiformis*, and the control treatments (Figure 5). Mitchell et al. (1999), in contrast, showed that *V. sativa* was reducing the soil moisture compared to treatments without CCs. The different observations can be explained as the water use of different CCs varies according to the degree of water stress, climate, and soil fertility (Meisinger et al. 1991).

The soil moisture in 2017 was generally higher than in the previous years, with subtle differences between the CC treatments, but relative differences between years were similar. This leads to the conclusion that the impact of CCs on the soil moisture increases under dry conditions, an effect which was also noticed by Mitchell et al. (1999).

Information about the water deficit tolerance (Figure 1), the soil moisture values (Figure 5), the weed biomass, and coverage (Figures 3 and 4), it is necessary to choose appropriate CCs to combine their advantages. *A. strigosa*, thereby, seems to condense several benefits. From the results of the greenhouse experiment, it was observed that *A. strigosa* showed greater water deficit tolerance as compared to *S. alba*. Although this could not be proven under field conditions. However, *A. strigosa* did not develop sufficiently under dry conditions in both field experiments, also concerning other CC treatments. Nevertheless, it was still able to reduce the weed cover and biomass compared to the control and increased the soil moisture. In the wet season 2017, *A. strigosa* showed the highest soil cover with 92% resulting in the highest weed suppression and minor effects on soil water content. *S. alba* showed a similarly high weed suppression potential but simultaneously exhibited the highest sensitivity to drought in the greenhouse.

In conclusion, in the greenhouse under controlled conditions, CCs showed different water stress tolerances. CC biomass production under dry field conditions could not be attributed to CC water stress tolerance, as CCs with a low water deficit tolerance in the greenhouse produced the highest dry matter in the field. In the field, interrelations seem to be more complex and CC germination and establishment, important factors of the weed suppression potential, depend on several abiotic and biotic factors as well as management practices (as, e.g., seed density and depth).

Generally, when CCs produce a low amount of biomass, as, e.g., in water-limited areas or within years of low precipitation in fall, their benefits like weed suppression are a lot smaller than in humid areas or seasons (Nielsen et al. 2015). Taking into account the water demand and the specific weed

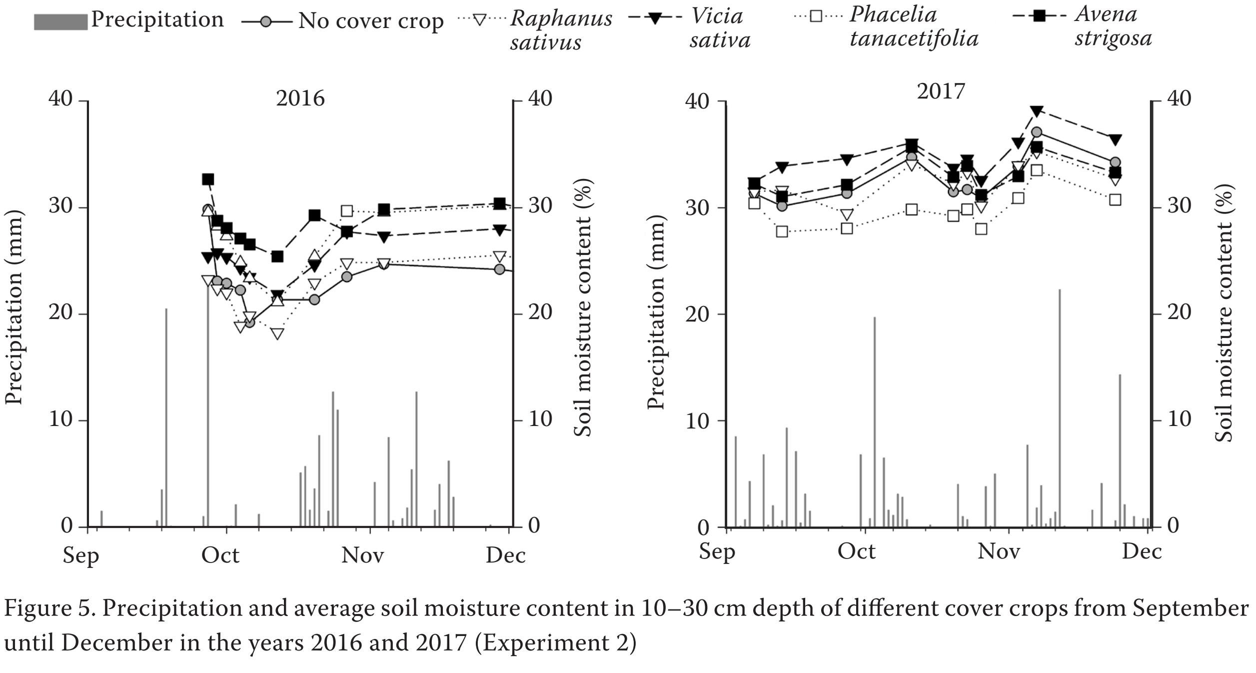

Figure 5. Precipitation and average soil moisture content in 10–30 cm depth of different cover crops from September until December in the years 2016 and 2017 (Experiment 2)

suppression mechanisms of CCs, therefore, may contribute to reducing the depletion of soil moisture and improves the success of weed control by CCs also under water-limited circumstances. Still, further research is needed to gather more information on CC species for specific requirements related to different soil types and climate conditions.

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