Nutr Cycl Agroecosyst
https://doi.org/10.1007/s10705-024-10370-9

ORIGINAL ARTICLE

Impact of mechanical weed control on soil N dynamics, soil moisture, and crop yield in an organic cropping sequence

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Received: 31 December 2023 / Accepted: 5 July 2024

Abstract Mechanical weed control is a major element of weed suppression in organic farming systems. In addition to the direct effect on weed growth, mechanical weeding, such as harrowing or hoeing, is known to induce side effects on several soil- and crop-related properties. In this study, we investigated the impact of mechanical weeding on soil mineral nitrogen (SMN), soil moisture, and crop yield in an organic crop rotation of grass-clover (*Lolium multiflorum* Lam., *Trifolium pratense* L.), silage maize (*Zea mays* L.) and winter barley (*Hordeum vulgare* L.). The experiment was conducted in two consecutive years (2021, 2022), where each crop was grown in each year on a Plaggic Anthrosol with sandy loam in North-West Germany. Two weed control treatments (mechanical: harrowing, hoeing; chemical: herbicide application) were implemented in a randomized block design with four replications. Greater net nitrogen (N) mineralization in maize compared to winter barley were attributed to the incorporation of grass-clover residues before sowing of maize and greater mineralization potential during the maize growing season. Higher weed growth in maize after mechanical weeding resulted in a reduction of up to 47% in SMN content in the topsoil. In barley, no differences in weed suppression were observed between the treatments and only small effects on SMN were determined after mechanical weeding. The soil water content in the mechanically weeded plots was significantly higher at several events in both years and for both crops, which was attributed to increased water infiltration by disrupting the soil crust. Neither crop yield nor N uptake in harvest products was affected by the different treatments.

Keywords Harrowing · Hoeing · N mineralization · Organic farming · Pesticide free conventional farming

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Introduction

Nitrogen (N), the essential nutrient for arable crops, is often limited in organic farming systems; however, from a global perspective, reactive N input in cropping systems has expanded since the production of mineral N fertilizers started (Erisman et al. 2013; Döring and Neuhoff 2021; Liang et al. 2021). Due to the use of only non-synthetic N inputs, managing the available resources (e.g. symbiotically fixed N_2 from legumes, livestock manures) most efficiently is

Published online: 08 August 2024

crucial in organic farming systems in order to provide sufficiently high yields (Wilbois and Schmidt 2019; Hülsbergen et al. 2023).

Another challenge for stabilizing yields in organic cropping systems is the competition for resources between arable crops and weeds (Bond and Grundy 2001; Gaba et al. 2014). Weeds can pose a high risk to the yield of the crop depending on the weed species, crop, and environmental conditions (Oerke 2006; Gaba et al. 2014). In organic farming systems, weed management is often carried out by various indirect (i.e., cropping sequence, row width, sowing date, choice of cultivar) and direct (i.e., mechanical weeding with harrows or hoes, thermal weeding) measures (Bond and Grundy 2001; Jha et al. 2017). For both, chemical and mechanical weed control methods, negative and positive effects on crop and weed development (in addition to their impact on the environment and biodiversity) have been reported (Ryan et al. 2010; Manalil et al. 2011; Heap and Duke 2018). As mechanical weeding is often less efficient in controlling weeds than herbicide application, particularly within the rows, crop yields may be reduced due to increased competition between the crop and weeds (Pannacci and Tei et al. 2014). Additionally, van der Werf et al. (1991) argued that mechanical weeding enhances the risk of root injuries, which can result in reduced N uptake by plants and thus, reduce N content in harvest products.

Soil disturbance (i.e., tillage) potentially affects soil N dynamics by increasing soil temperature and soil aeration and physically breaking up soil macroaggregates (Reicosky et al. 1997; Silgram and Shepherd 1999). Previously protected soil organic matter is than exposed to microbial consumption, which leads to an increase in N mineralization rates (Franzluebbers 1999; Six et al. 2000; Calderón et al. 2001). Little is known if measures involving superficial soil disturbance, such as mechanical weeding, also affect soil N dynamics (Steinmann 2002; Gilbert et al. 2009). According to Gilbert et al. (2009) and Steinmann (2002), mechanical weeding could have a beneficial impact on crop growth by synchronizing N mineralization and crop N demand. However, in both studies, mechanical weeding performed by harrowing did not substantially increase N mineralization in spring wheat and did not significantly affect grain yield (Steinmann 2002; Gilbert et al. 2009). Calderón et al. (2000) and Steinmann (2002) argued that shallow treatments, such as harrowing, are less likely to affect soil N dynamics in soils with a history of intensive tillage because microorganism communities have already adapted to continual loosening. The impact of mechanical weed control on SMN was evaluated in studies that exclusively examined wheat varieties (winter and spring) grown in rotations with oilseed rape or soybean (Steinmann 2002; Thomsen & Sørensen 2006; Gilbert et al. 2009). Gilbert et al. (2009) argued that N immobilization occurred in their study due to N limited decomposition of soybean residues with a C/N ratio $>$ 30. This indicates a lack of synchronization between the N demand of the succeeding crop (spring wheat) and decomposition of soybean residues. Grass-clover leys, such as Italian ryegrass–red clover, accumulate high amounts of N due to biological N fixation by clover (Eriksen and Jensen 2001; Anglade et al. 2015). Termination of grass-clover leys (i.e., by ploughing) usually leads to a fast decomposition of N-rich ley residues, resulting in high N mineralization rates (Djurhuus and Olsen 1997; Eriksen and Jensen 2001; Hansen et al. 2021). Maize is often grown following grass-clover leys due to its capacity for high N uptake, which renders it an appropriate crop with regard to the synchronization of N mineralization and crop N demand (Herrmann and Taube 2005; Hansen and Eriksen 2016). Furthermore, mechanical weed control in maize commonly involves both hoeing and harrowing, leading to greater soil disturbance compared to exclusively harrowing. Steinmann (2002) and Gilbert et al. (2009) hypothesized that harrowing or hoeing might stimulate N mineralization under conditions with higher inputs of organic matter. However, it has not been investigated whether mechanical weed control performed by harrowing and hoeing has a further effect on SMN dynamics after incorporating N-rich leys in spring, followed by maize.

Several authors have reported that the temporal and spatial variability in soil water content, combined with the natural variability of the main soil characteristics, often mask the effects of agricultural practices (Lampurlanés et al. 2001; Green et al. 2003; Ugarte Nano et al. 2016). Nevertheless, soil loosening by tillage is known to increase water infiltration temporarily, while over time the soil will naturally reconsolidate (Ahuja et al. 1998; Lampurlanés et al. 2001; Ugarte Nano et al. 2016). Furthermore, water infiltration alters the pore size distribution and dispersion of soil aggregates, which leads to crusting at the soil surface through the impact of rain drops (Valentin and Bresson 1992; Ahuja et al. 1998). Soil surface crusts then reduce water infiltration and enhance soil erosion and run-off (Valentin and Bresson 1992). Mechanical weeding could serve as a management technique to prevent the aforementioned outcomes by disrupting the soil crust. There is a lack of knowledge regarding the effect of mechanical weeding on soil N dynamics and soil moisture in an organic farming system with legume-rich leys (Gilbert et al. 2009; Ugarte Nano et al. 2015). In the context of efficient use of resources and increasing occurrence of extreme weather events (e.g., drought, heavy rainfall), the impact of mechanical weeding needs to be further examined and reconsidered.

The aim of this study was to investigate how superficial soil disturbance caused by mechanical weeding compared to non-inversive herbicide application affects short-term SMN dynamics, soil moisture, crop yield, and N uptake in an organic cropping sequence. The following hypotheses were addressed:

(1) Mechanical weed control performed by harrowing and hoeing compared to a control treatment without soil disturbance increases SMN in maize by further stimulating N mineralization. In winter barley, mechanical weed control has no effect on SMN dynamics compared to the control treatment due to only shallow soil disturbance by harrowing and low soil temperatures at the time of harrowing.
(2) The stimulated N mineralization in maize after mechanical weeding leads to a higher N uptake in plant biomass. No difference in N uptake for winter barley between mechanical weeding and the control treatment is expected. Maize biomass and barley grain yield are expected to be lower in the mechanical treatment as mechanical weeding may have a lower efficiency in weed control compared to the chemical control.
(3) Soil moisture is higher after mechanical weeding, in both maize and winter barley, compared to the control treatment due to improved water infiltration by breaking the soil crust.

Materials and methods

Study site

The field trial was conducted within the drinking water abstraction area Belm–Nettetal at 52.3° N, 8.1° E in North-West Germany (Fig. 1).

The climate is classified as temperate oceanic (Cfb) (Peel et al. 2007) with a mean annual air temperature of 10.0 °C and a mean annual precipitation sum of 818 mm (long-term average from 1991 to 2020 (Agronomy Kiel 2023)). The study site is

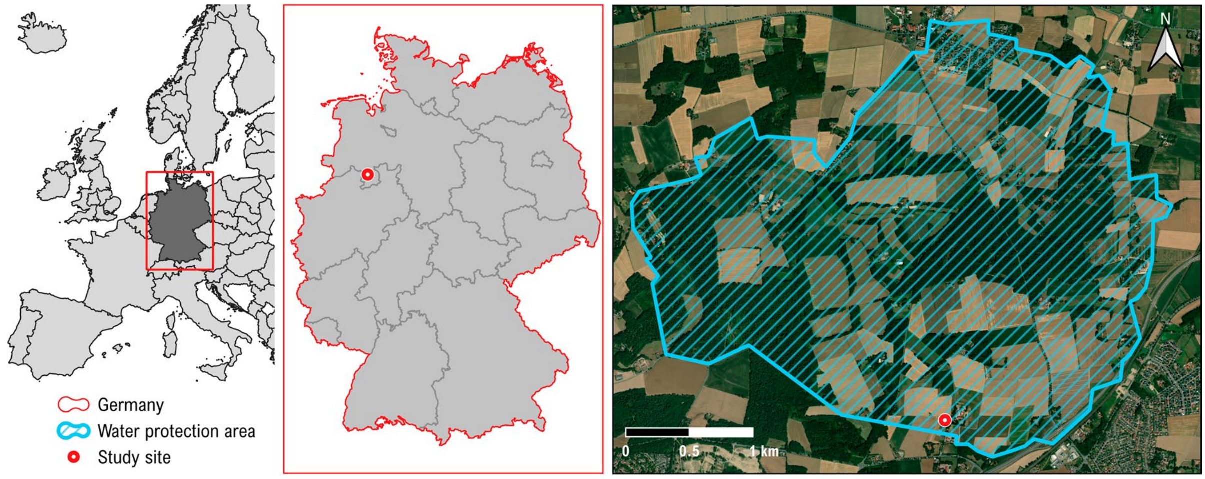

Fig. 1 Location of the study site within a German water protection area in Central Europe. The predominant land use (58%) is arable farming (data source: Esri 2023)

characterized by a Plaggic Anthrosol (IUSS Working Group WRB 2015) with a sandy loam texture (55/39/6% of sand/silt/clay). In the topsoil (0–30 cm), at the beginning of the experiments, the pH (suspended in $CaCl_2$) was 6.4, and plant available phosphorus and potassium contents were 92.7 mg kg^{-1} and 138.2 mg kg^{-1}, respectively. The average soil organic carbon (C) content was 11.44 g kg^{-1}, and the average total N content was 0.95 g kg^{-1}, resulting in a C/N ratio of 11.8. Before the trial period, the study site was managed conventionally until 2019 as part of a previous pilot and demonstration project (Kühling et al. 2021). Since 2020, field management has been performed according to the EU directive on organic farming (EU 2018).

Experimental setup

The treatments and measurements were performed on silage maize and winter barley in a grass-clover–silage maize–winter barley–spring oat crop rotation in 2021 and 2022. The field trial is divided into four main plots of equal size with one crop per block. This allows for the retention of the crop rotation and the growth of each crop in each year. To investigate the effect of mechanical weeding on soil N dynamics and soil moisture, mechanical weed control performed by harrowing or hoeing was compared to a control treatment without soil disturbance. Although herbicide application is not in line with the EU regulation on organic farming, it was chosen as the control treatment because it is the most commonly used method of weed control without soil disturbance. The two treatments (mechanical weeding: harrowing or hoeing; chemical weeding: herbicide) were arranged in a randomized block design with four replications in maize and barley. The plot size was 30 m^2 (3 m × 10 m) for both crops and years. Tillage was performed before sowing with a shallow moldboard plough (up to 20 cm soil depth). Afterwards, a rotary cultivator was used for seedbed preparation. N application was carried out with organic fertilizer (biogas digestate from an organic certified biogas plant) after analyzing for NO_3^- and NH_4^+ contents each year. Nitrogen application rates were calculated according to the German fertilizer ordinance, where crop-specific N needs regarding yield expectations, previous crop effects, soil mineral N at the beginning of the growing season, location in nitrate-sensitive areas and previous organic fertilizer application rates are considered (DüV 2017). In both years and treatments, 30 kg N ha^{-1} was applied to silage maize at sowing, and 90 kg N ha^{-1} was applied to winter barley 20 days before the first mechanical weeding. Additional fertilization of basic nutrients (K, Ca, Mg, S) was performed as usual upon demand within each crop in line with the EU directive on organic farming (EU 2018). Harrowing was carried out with a tine harrow (APV, Austria), and hoeing was carried out with a sweep share hoe (Schmotzer, Germany). Every mechanical weeding activity was done with moderate speed: 5–7 km h^{-1} for harrowing and 4 km h^{-1} for hoeing—with a harrowing and hoeing depth of 1–3 and 3–5 cm, respectively. Detailed information on sowing as well as on harrowing, hoeing, and harvesting dates is given in Table 1.

For the plots with chemical weed control, a combination of postemergence herbicides (maize: 80 g ha^{-1} Mesotrione, 504 g ha^{-1} Dimethenamid-P, and 450 g ha^{-1} Terbuthylazin; barley: 50 g ha^{-1} Pinoxaden, 12.5 g ha^{-1} Cloquintocet-mexyl, 3.75 g ha^{-1} Florasulam, and 45 g ha^{-1} Clopyralid) was applied in 2021 and 2022.

Soil and plant analyses

For investigating SMN, disturbed soil material was taken from 0–5 to 5–20 cm soil depth as mixed samples from eight randomly distributed penetrations per plot and sampling date. The soil samples were collected directly before harrowing or hoeing and two and four days afterwards, respectively. Additionally, soil samples were taken at greater depths (0–30, 30–60, and 60–90 cm) before sowing and after harvest. Before analyzing the NH_4^+ and NO_3^- contents via extraction with 0.01 M $CaCl_2$, the soil samples were stored at − 18 °C. The concentrations of NH_4^+ and NO_3^- in the extracts were determined with a spectrophotometer (Lambda 25, Perkin Elmer, USA). Additionally, a subsample of each sample was dried at 105 °C for 24 h to ascertain gravimetric soil water content. To calculate the volumetric water content (VWC), the bulk density of the 0–5 and 5–20 cm soil layers was determined by collecting undisturbed soil cores (100 cm^3) before and after mechanical weed control in each crop in 2021 from 6 subsamples per experimental area. Barley was harvested at maturity with a plot combine harvester. After

Table 1 Information on sowing, harrowing, hoeing, and harvesting for both crops and years. Growth stages according to BBCH (Meier 2001)

	Stage		2021	2022
Maize				
Previous crop			Grass-clover	Grass-clover
Sowing			14.05	06.05
		Cultivar	Rudint	Rudint
		Row width cm	75	75
		Seeds m^{-2}	9	9
Harrowing	00–07		20.05	10.05
Hoeing	13		07.06	25.05
Hoeing	15–17		23.06	13.06
Harvest	85		21.09	20.09
Barley				
Previous crop			Maize	Maize
Sowing			12.10.2020	01.10.2021
		Cultivar	Quadriga	Quadriga
		Row width cm	12.5	12.5
		Seeds m^{-2}	350	350
Harrowing	21		25.03	21.03
Harrowing	27–29		20.04	13.04
Harvest	92		16.07	12.07

combine-harvesting, a grain subsample was taken per plot to determine the dry matter content by drying the grain for 48 h at 85 °C. Maize was harvested manually as whole plants at two different spots of 2 m^2 per plot and was subsequently chopped. The total N content in plants (maize) and grains (barley) was analyzed via near-infrared spectroscopy. Weed coverage was determined directly before each mechanical weed control and at harvest using a Goettinger Schaetzrahmen (0.1 m^2) at three different spots per plot, which were marked before the first mechanical weed control.

Calculations and statistics

Soil mineral N in 0–5 and 5–20 cm soil depth was calculated by computing the original equivalent soil masses according to Ellert and Betany (1995) and Lee et al. (2009) to respond to changing bulk densities from mechanical weeding. Net N mineralization was calculated from starting point $t0$ (i.e., sowing) to endpoint $t1$ (i.e., harvest) using Eq. (1) according to Kühling et al. (2023):

$$netNmin_{t1-t0} = \left(Nuptake_{t1} - Nfert\right) + \left(SMN_{t1} - SMN_{t0}\right) \quad (1)$$

where Nuptake is the N accumulation in aboveground biomass, Nfert as the amount of N fertilizer added and SMN represents the soil mineral nitrogen content in 0–90 cm at the respective time points.

Statistical analyses were performed with R (R Core Team 2023) to conduct an analysis of variance followed by a Tukey HSD test ($p \leq 0.05$) for SMN content, net N mineralization, VWC, weed cover, yield, and N uptake as a linear mixed effects model. For SMN and VWC, treatment, days after mechanical weeding, and year were assumed to be fixed and plot nested within block was assumed to be random by using the R packages nlme (Pinheiro et al. 2023), emmeans (Lenth 2023), and multcomp (Piepho 2004). Furthermore, this model was tested separately for each crop, soil depth and date of weed control. The weed cover data was transformed using the square root function and analysis was performed separately for each year to achieve homogeneity of variance.

Results

Sum of precipitation in 2021 was 20% lower than the long-term average (LTA) with dry months, particularly during summer and fall (Fig. 2).

In 2022, sum of precipitation was also reduced (−26%) compared to the LTA, while high rainfall was observed in February. The mean annual air temperature in 2022 was 1.1 °C warmer, whereas the temperature in 2021 was similar (−0.09 °C) to the LTA.

Soil mineral N dynamic

The SMN content differed between crops, years, and days of measurement (Table 2). For maize in 2021, three events were observed where the different weed control had a significant effect on SMN content in 0–5 cm soil depth between the rows.

Soil mineral N was 28, 45 and 47% lower four days after the second and two and four days after the third mechanical weeding compared to the

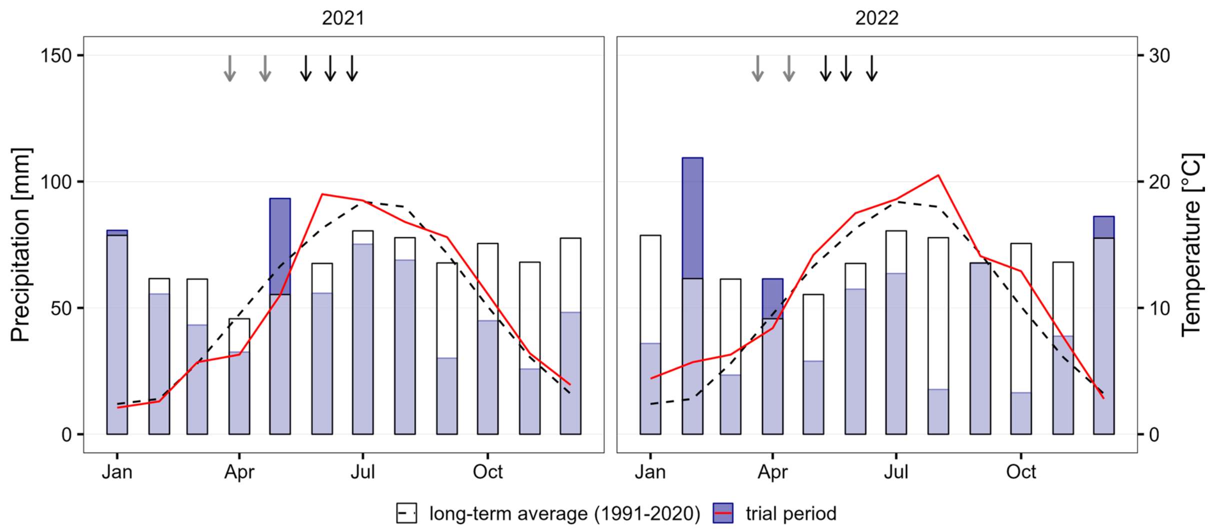

Fig. 2 Sum of precipitation (bars) and mean air temperature (lines) during the trial period (2021, 2022) in comparison to the LTA (1991–2020) on a monthly basis at the study site. Arrows mark the week of mechanical weed control (grey for weed control in barley; black for weed control in maize)

chemical treatment, where SMN was 15.29, 23.14 and 32.59 kg ha^{-1}, respectively (Fig. 3).

In 2022, there was a significant effect of the different treatments on SMN content (0–5 cm soil depth) observed only four days after the first mechanical weeding in maize, where SMN content was significantly lower in the mechanical treatment (12.60/16.05 kg ha^{-1}; mech/chem). In both years and treatments, SMN content (0–5 cm soil depth) increased from the first (12.23 kg ha^{-1}) to the third weed control (26.5 kg ha^{-1}). This increase also occurred in 5–20 cm soil depth, where the average SMN content was 52.96 kg ha^{-1}. Harrowing or hoeing did not significantly affect SMN content in 5–20 cm soil depth.

In winter barley, the mean SMN content was 6.71 kg ha^{-1} in 0–20 cm soil depth with 2.76 and 3.95 kg ha^{-1} in 0–5 and 5–20 cm soil depth, respectively. Mechanical weeding led to a marginal but significant increase in SMN content (+0.21 kg ha^{-1}) at the second weeding passage compared to the undisturbed plots (mean SMN content of 1.15 kg ha^{-1}) in 0–5 cm soil depth, while no effect was detected in 5–20 cm soil depth (Table 2).

In our study, the calculated net N mineralization for soil depth 0–90 cm from sowing to harvest was not significantly affected by the different weed control treatments for both crops and years (Table 3).

Net N mineralization rates in maize show a distinctive variation between the years and treatments and are in general higher compared to net N mineralization in winter barley, which was especially low in 2022.

Soil moisture response to weed control

The different weed control treatments significantly affected soil moisture. In maize, mechanical weed control led to higher VWC in both soil depths, with differences between years and days of measurement (Table 2). The VWC decreased from the first to the third mechanical weeding in both soil layers in 2021. This effect occurred for both treatments (mechanical and chemical), with the strongest decrease occurring at the third mechanical weeding in 2021. However, VWC in the mechanical treatment remained higher than in the undisturbed plots with herbicide application (Fig. 4).

In 2022, VWC increased from the first to the second and decreased from the second to the third weeding in 0–5 cm soil depth, but VWC at the first and third mechanical weeding were on a similar level (12.31/12.11%; first/third). Precipitation sums between the mechanical weeding dates were higher in 2021 compared to 2022, which is also reflected in the

Table 2 *P* values of the analyses of variance

	Soil mineral nitrogen (kg ha^{-1})				Volumetric water content (%)			
	Maize		Barley		Maize		Barley	
	0–5 cm	5–20 cm	0–5 cm	5–20 cm	0–5 cm	5–20 cm	0–5 cm	5–20 cm
1st weeding								
T	0.159	0.408	0.902	0.792	0.467	**0.019**	**< 0.001**	**< 0.001**
DAM	**< 0.001**	0.489	0.403	**0.002**	**< 0.001**	**< 0.001**	0.179	**0.032**
Y	**< 0.001**	0.126	0.184	0.604	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
T × DAM	0.732	0.927	0.793	0.463	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
T × Y	0.482	0.227	0.262	0.574	**0.044**	0.269	0.852	0.396
DAM × Y	**0.018**	0.041	0.211	0.090	**< 0.001**	0.182	**< 0.001**	**< 0.001**
T × DAM × Y	**0.028**	0.171	0.221	0.829	0.257	0.859	0.716	0.795
2nd weeding								
T	0.337	0.517	**0.040**	0.329	**0.006**	0.067	**0.003**	**< 0.001**
DAM	0.059	**< 0.001**	0.068	0.100	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
Y	**< 0.001**	0.383	**0.008**	0.518	**0.013**	**0.002**	**< 0.001**	**< 0.001**
T × DAM	**0.032**	0.750	0.658	0.604	**< 0.001**	**< 0.001**	**< 0.001**	**0.007**
T × Y	0.187	0.957	0.616	0.147	0.61	0.564	**0.036**	0.183
DAM × Y	**< 0.001**	0.213	0.210	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**	**< 0.001**
T × DAM × Y	0.789	0.288	0.449	0.204	0.32	0.291	0.062	0.352
3rd weeding								
T	**0.009**	0.681			**< 0.001**	**0.003**		
DAM	0.141	0.805			**< 0.001**	**< 0.001**		
Y	**< 0.001**	0.309			**< 0.001**	**0.003**		
T × DAM	0.096	0.811			**0.024**	**0.009**		
T × Y	0.050	0.633			**0.031**	0.450		
DAM × Y	**< 0.001**	0.277			**< 0.001**	0.069		
T × DAM × Y	0.463	0.475			0.416	0.844		

Bold numbers ($p \leq 0.05$) indicate the significant effects of the tested variables (T = treatment; DAM = days after mechanical weeding; Y = year) and their interactions

mean VWC for all sampling dates and treatments in 0–20 cm soil depth (17.61/15.37%; 2021/2022).

For barley, VWC in 0–5 cm soil depth was significantly higher in the mechanical (18.64%) than in the chemical treatment (17.82%) with differences between years and days of measurement (Fig. 5).

In 5–20 cm soil depth, harrowing led to a significantly higher VWC (+ 2.39%) four days after the first mechanical weeding in both years. In contrast, VWC was significantly lower in the mechanical treatment (-1.53%) than in the undisturbed plots at the second weed control, which was more pronounced in 2022 than in 2021. Precipitation sums between the mechanical weeding dates were higher in 2022 compared to 2021, but precipitation was distributed more evenly between the dates in 2021. Nevertheless, mean VWC in 0–20 cm soil depth was similar in both years (19.74/19.39%; 2021/2022).

Weed suppression

Both treatments (mechanical and chemical) did not completely suppress weed growth. In maize, weed cover was significantly higher for the mechanical treatment at the third measure (12.67%) and at harvest (10.07%) in 2021 than for the chemical treatment (1.42/1.18%), while no significant effect of the different treatments on weed cover was observed in 2022 (2.88/3.6%; chem/mech) (Fig. 6).

The variation in weed cover was greater for the mechanical treatment, particularly in 2021, at the third mechanical weeding and in 2022, at harvest, where weed cover ranged from 1.27 to 21.00% (2021) and from 0.67 to 35.23% (2022). Since the weed cover was 0% at the first weed control (blind harrowing) for both treatments and years, this value is not displayed in Fig. 6. The weed cover increased in maize during

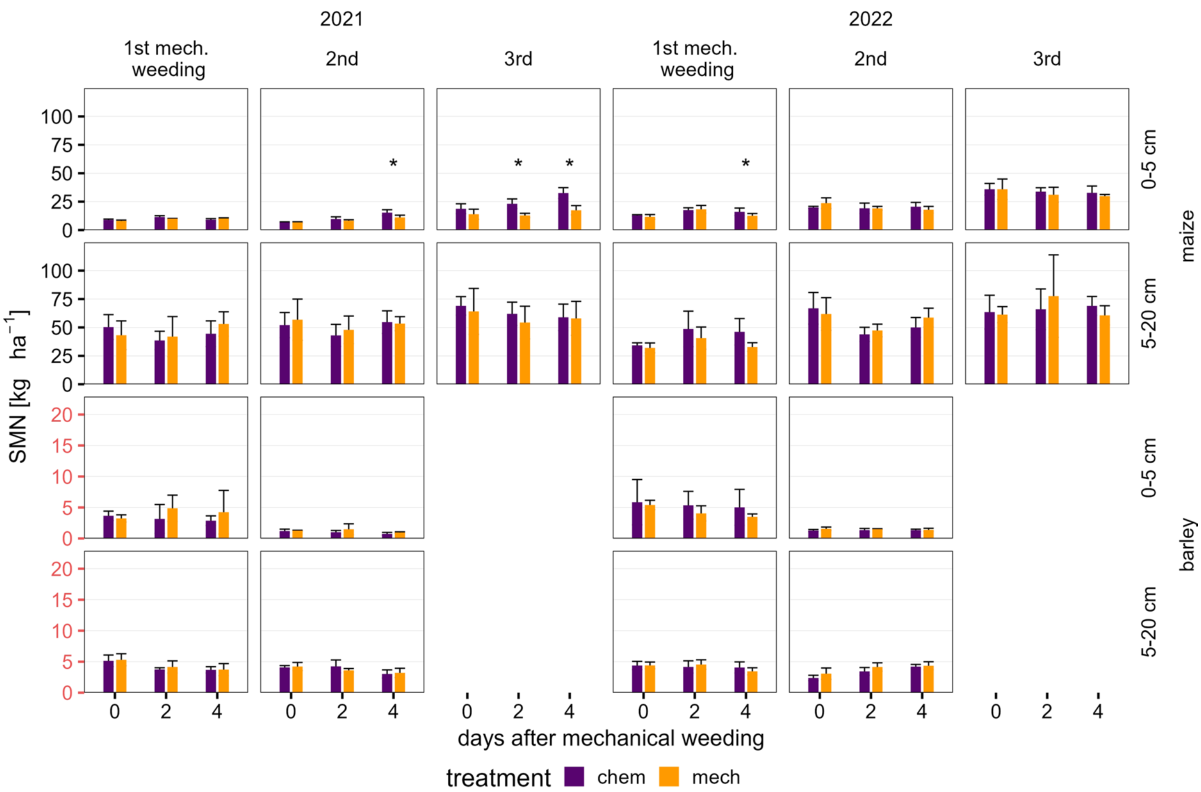

Fig. 3 Mean soil mineral nitrogen (SMN) content (bars) with standard deviation (error bars) in 0–5 and 5–20 cm soil depth directly before each mechanical weeding and after two and four days for both years, crops and treatments (mechanical: mech; chemical: chem). * indicate a significant difference between the means of the two treatments ($p \leq 0.05$) on that day

Table 3 Net nitrogen (N) mineralization from sowing to harvest of maize and barley

Net N mineralization (kg ha^{-1})							
		2021		2022		Mean	
Maize	Treatment						
	Chemical	171.50	(±34.60)	229.68	(±15.89)	200.59	(±39.85)
	Mechanical	183.02	(±33.53)	263.61	(±64.95)	223.31	(±64.38)
	p-value						*0.25*
Barley	Chemical	6.75	(±14.06)	−0.16	(±8.73)	3.30	(±11.45)
	Mechanical	9.64	(±17.68)	−3.15	(±4.96)	2.33	(±12.77)
	p-value						*0.93*

the treatment and growing season, respectively. Most frequently observed weed species in maize were *Chenopodium album* L., *Matricaria chamomilla* L., *Poa annua* L., *Stellaria media* L. Vill. *Lolium multiflorum* Lam., and *Viola arvensis*.

In barley, there was no significant difference in weed cover between the two weed control treatments in either year (6.16/6.31%; chem/mech). On average, weed cover was lower in 2021 (3.78%) when compared to 2022 (8.69%), and increased from the first weeding (3.21%) to harvest (10.55%). The weed species that were most frequently observed in barley were *Viola arvensis*, *Matricaria chamomilla* L., *Poa annua* L., *Stellaria media* L. Vill., and *Chenopodium album* L..

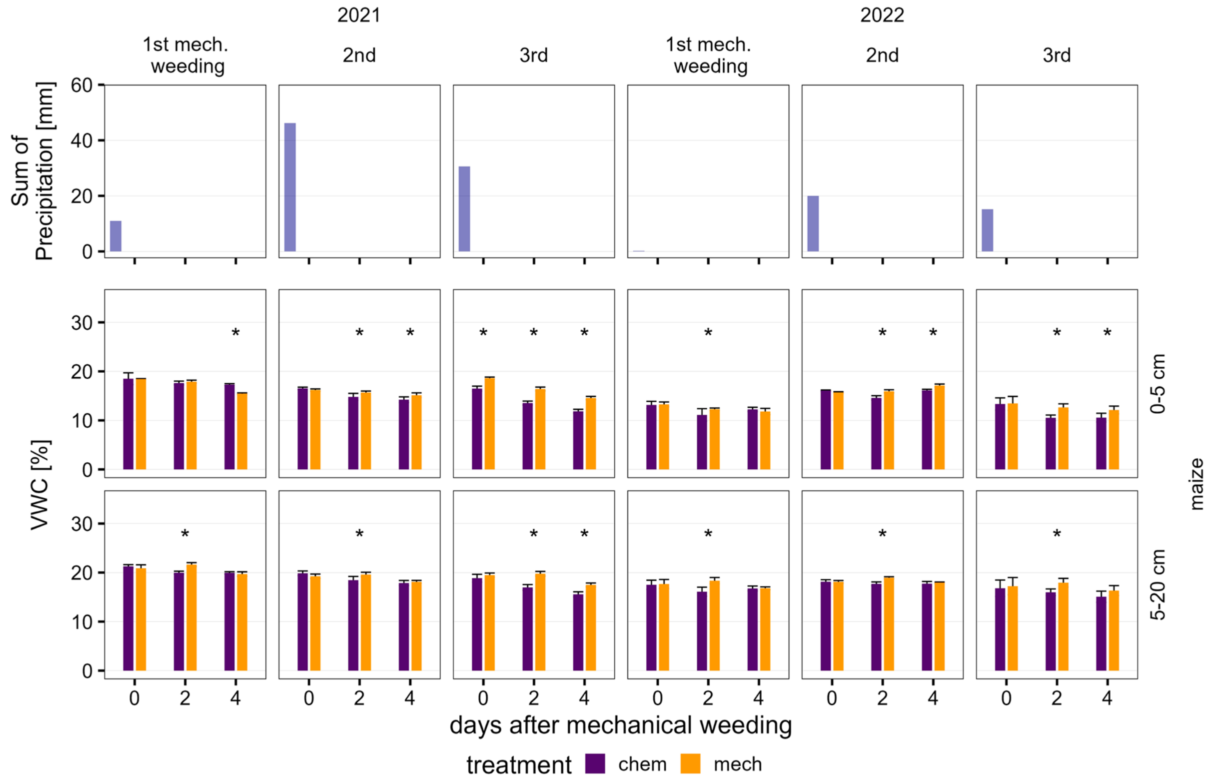

Fig. 4 Mean volumetric water content (VWC; bars) with standard deviation (error bars) in 0–5 and 5–20 cm soil depth with precipitation sums between the mechanical weeding dates for both years and treatments (mech: mechanical; chem: chemical) in maize. * indicate a significant difference between the means of the two treatments ($p \leq 0.05$)

Yield and N uptake

Neither grain yield (winter barley) or biomass yield (silage maize) nor N uptake in these harvest products were significantly affected by the different weed control treatments in both years (Table 4).

Discussion

Mechanical weeding did not stimulate soil N dynamics

In both years, a higher SMN in 0–20 cm soil depth was observed for maize (mean of 70.82 kg ha^{-1}) compared to winter barley (mean of 6.71 kg ha^{-1}). Plaggic Anthrosols with a sandy soil texture typically show a lower N mineralization potential from the slowly decomposable N pool compared to loess soils (Heumann et al. 2002; Springob and Kirchmann 2003). In our study, the incorporation of grass-clover residues with a C/N ratio of 13.7 before the sowing of maize contributed to a fast mineralizable N pool and led to high N mineralization rates. Furthermore, different soil temperatures during the measurements (barley in spring, maize in summer) may also have contributed to the difference in N mineralization in the field between the crops (Risch et al. 2019). Wider rows in maize (75 cm) compared to barley (12.5 cm) expose more uncovered soil surface to sunlight, resulting in faster warming (Sharatt and McWilliams 2005). For maize, a lower SMN content in 0–5 cm soil depth after mechanical weeding was observed at three events at the end of the treatment period in 2021 and at one event after the first harrowing in 2022. This decrease in SMN content indicates that harrowing and hoeing did not further stimulate N mineralization in maize. Gilbert et al. (2009) and Owen et al. (2006) attributed the reduced SMN content after mechanical weeding to N immobilization processes.

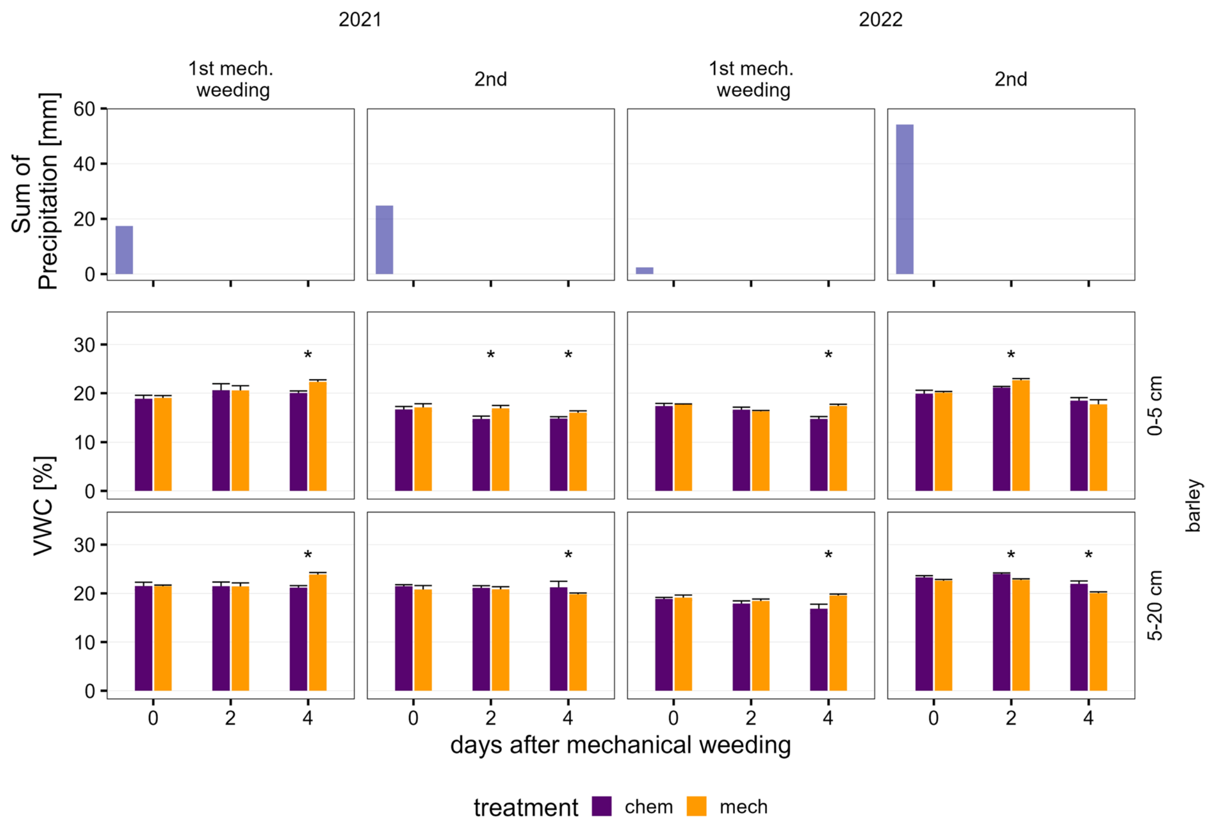

Fig. 5 Mean volumetric water content (VWC; bars) with standard deviation (error bars) in 0–5 and in 5–20 cm soil depth with precipitation sums between the mechanical weeding dates for both years and treatments (mech: mechanical; chem: chemical) in winter barley. * indicate a significant difference between the means of the two treatments ($p \leq 0.05$)

In an experiment where tillage was simulated by sieving intact soil cores, Franzluebbers (1999) argued that N was temporary immobilized due to increased carbon mineralization of crop residues with a wide C/N ratio (> 20) under N-limited conditions. However, the incorporation of legume crop residues with a narrow C/N ratio typically leads to a high N release (Hansen et al. 2021), which was also reflected in high net N mineralization in our study. Compared to the chemical control, significantly higher weed coverage was determined for mechanical weeding in 2021 after the third treatment and at harvest. Low temperatures at the time of sowing could have delayed maize development and benefitted weed growth. Therefore, the lower SMN content in the mechanical treatment compared to the chemical control around the third treatment (hoeing) is attributed to a higher N uptake by weeds in the mechanically weeded plots. In 2022, no difference in weed growth between the treatments was observed, which was also reflected in similar SMN contents, suggesting that the lower SMN content after mechanical weeding in 2021 did not result from temporary N immobilization.

In winter barley, low net N mineralization was observed in both treatments. Soil N mineralization starts at the beginning of spring when the soil temperature increases and there is sufficient soil moisture. While high SMN would be required to meet the increased N demand of winter barley during stem elongation in early spring, high N mineralization rates usually occur in late spring and early summer, respectively. This indicates a general poor synchronization between the N demand of winter barley and soil N mineralization (Steinmann 2002) and was also expected in this study. Mechanical weeding in barley led to a minor and therefore agronomically negligible increase in SMN (+0.21 kg ha^{-1}) in 0–5 cm soil depth after the second mechanical weeding,

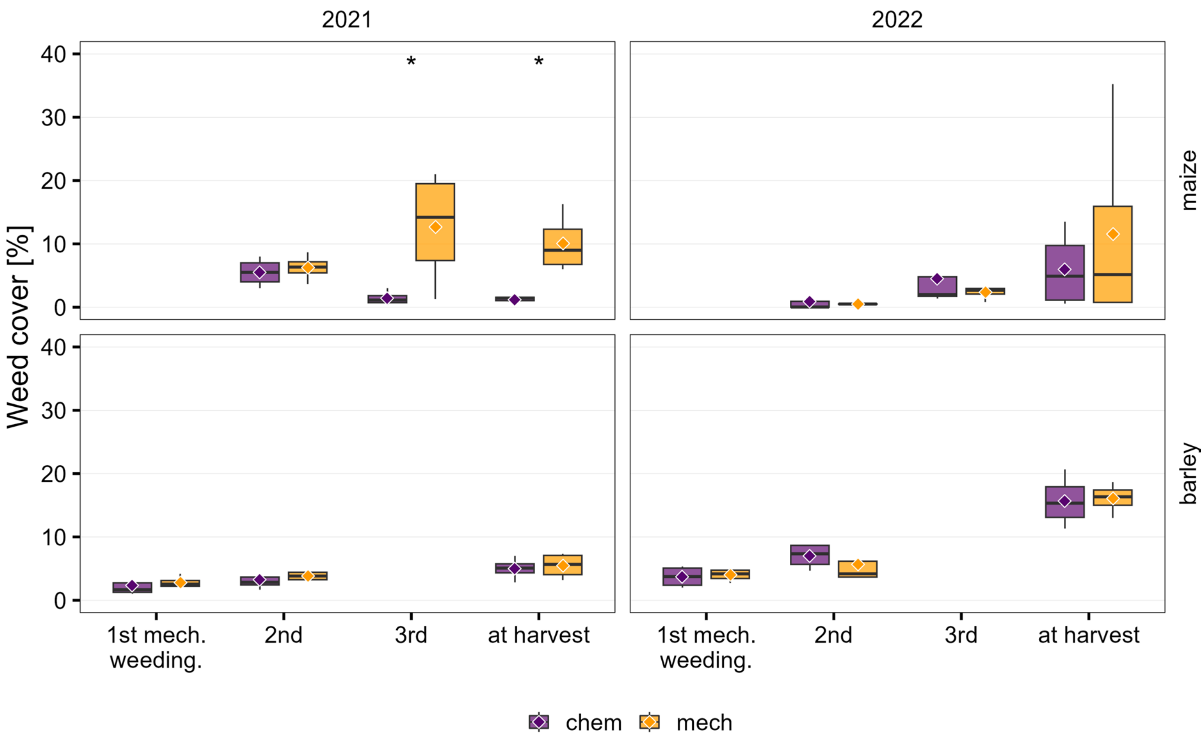

Fig. 6 Weed cover as boxplots with mean values (rhombus) before each mechanical weeding and at harvest for both years, crops, and treatments (mech: mechanical; chem: chemical). * indicate a significant difference between the means of the two treatments ($p \leq 0.05$)

Table 4 Yield and nitrogen (N) uptake in harvestable products (grain for winter barley [86% dry matter (DM)] and shoot biomass for silage maize [100% DM])

		Yield (t ha $^{-1}$)					
		2021		2022		mean	
Maize	Treatment						
	Chemical	18.88	(±3.07)	20.56	(±2.06)	19.72	(±2.59)
	Mechanical	19.14	(±1.89)	20.24	(±3.34)	19.69	(±2.58)
	p-value					*0.98*	
Barley	Chemical	3.61	(±0.28)	4.34	(±0.46)	3.97	(±0.52)
	Mechanical	3.45	(±0.19)	4.24	(±0.06)	3.85	(±0.44)
	p-value					*0.26*	
		N uptake (kg N ha^{-1})					
		2021		2022		mean	
Maize	Treatment						
	Chemical	185.75	(±33.53)	205.68	(±12.51)	195.72	(±25.74)
	Mechanical	197.02	(±34.94)	211.36	(±55.58)	204.19	(±43.66)
	p-value					*0.66*	
Barley	Chemical	42.57	(±3.12)	41.50	(±5.06)	42.03	(±3.93)
	Mechanical	40.54	(±1.57)	40.89	(±0.99)	40.71	(±1.23)
	p-value					*0.35*	

confirming the results of Steinmann (2002), Thomsen and Sørensen (2006) and Gilbert et al. (2009), who also found only insignificant amounts of additional N after mechanical weeding. For mechanical weeding in barley, a tine harrow was used exclusively, which causes less soil disturbance than a hoe. However, hoeing did not increase N mineralization in maize and it is therefore unlikely that hoeing would have increased SMN in winter barley. Additionally, weed growth did not differ significantly between the treatments and years in winter barley and therefore did not distort the results for SMN, VWC, or grain yield. In this study, soil N dynamics were affected by the previous crop and climate conditions, while only indirect effects of mechanical weeding on SMN were observed in the form of stronger weed growth in one year and crop.

Mechanical weeding resulted in higher soil moisture

In both years, two (winter barley) to five (maize) events were observed where the VWC in 0–5 cm soil depth was higher in the mechanical treatment than in the chemical control. In maize, a slightly lower VWC was observed at the end of the treatment period in 2022 compared to 2021, which was attributed to lower precipitation between the mechanical weeding dates (Fig. 4). Several studies have linked higher soil water content to an interrupted capillary system via shallow tillage or to the presence of remaining crop residues, which reduces evaporation (Aase and Tanaka 1987; Pittelkow et al. 2015; Liebhard et al. 2022). In this study, the soil capillary system was already altered by shallow ploughing and the incorporation of previous crop residues in all years, crops, and treatments. This led to the assumption that the additional superficial soil disturbance by mechanical weeding only had a marginal effect on the soil capillary system at our study site (sandy soil and low clay content). Furthermore, row spacing affects evapotranspiration. Various studies have demonstrated that a reduction in row spacing decreases evaporation, while transpiration increases with increasing canopy height (Chen et al. 2010; Barbieri et al. 2012). In addition to higher temperatures when measurements were carried out in maize, wider rows compared to narrow rows in winter barley may have benefitted soil warming and increased evaporation, which is reflected in a lower mean VWC (16.49/19.56%; maize/barley). However, we did not measure evaporation or transpiration in association with the soil tillage system or treatment of weed control; thus, further investigations are necessary. Wider rows in maize may have led to a greater variation and stronger weed growth in 2021 in mechanically weeded plots, which can result in higher transpiration rates, as reported by Hunt et al. (2013). Nevertheless, our results indicate that weed coverage in maize did not affect soil water content, as a higher VWC was observed after mechanical weeding compared to the chemical control in 2021 and also in 2022, when weed growth was similar in both treatments. Greater weed growth in mechanically weeded plots in 2021 may have reduced evaporation through soil surface coverage, but as mentioned above, increased plant water uptake would mask this effect (van der Werf et al. 1991; Hunt et al. 2013).

Van der Werf et al. (1991) attributed a higher soil water content after mechanical weeding to improved water infiltration. Superficial soil disturbance following tillage (i.e., ploughing and seedbed preparation) could have been beneficial due to disrupting the soil crust after rainfall (Valentin and Bresson 1992; Ahuja et al. 1998). In both years and crops, precipitation occurred between sowing and the first mechanical weeding and presumably caused soil crusting. In contrast to the undisturbed control, mechanical weeding disrupted the soil crust, which improved rewetting conditions and resulted in an increased water infiltration when precipitation fell between the mechanical weeding dates (Figs. 4 and 5). This effect might become crucial on sandy soils, which are highly susceptible to drought and would benefit from improved rewetting conditions.

Mechanical weeding did not reduce crop yield compared to herbicide application

The impact of mechanical weeding, such as harrowing or hoeing, on cereal crop yield has been investigated in several studies (van der Werf et al. 1991; Steinmann 2002; Gilbert et al. 2009; Armengot et al. 2013). While some authors have observed lower yields when weed control was performed by mechanical weeding compared to herbicide application (Pannacci and Tei 2014), other studies found no significant differences in crop yield between mechanical weeding and herbicide use (Thomsen and Sørensen 2006; Armengot et al. 2013). Pannacci and Tei (2014) attributed lower maize yields in harrowed plots to incomplete weed suppression, while hoeing resulted in similar yields compared to the chemical treatment. In our study, no differences in crop yield were observed between mechanical weeding and chemical control for either maize or barley. Despite significantly higher weed growth in the mechanical treatment for maize in 2021, there was no yield reduction. As the field trial has been organically cultivated only since 2020, the conversion in management practices may not yet be reflected in the weed seed bank and weed pressure. Therefore, competition between crops and weeds was not particularly pronounced in this study. In a two-year study with spring wheat, Steinmann (2002) observed a slightly reduced N content in crop biomass in response to harrowing, which was assigned to reduced N uptake by damaged plants. In our study, no impact of mechanical weeding on crop N uptake was detected for either crop or year. These results confirm those of Gilbert et al. (2009), who found no difference in N uptake between the mechanical treatment and the undisturbed control. For maize, the biomass yield and N uptake was similar (Cougnon et al. 2018) or higher compared to conventional cropping conditions (Kayser et al. 2011; Hansen and Eriksen 2016), while winter barley grain yield was 28% lower than that observed in a conventional cropping system at the same site during previous rotational cycles (Kühling et al. 2021). A meta-analysis by Seufert et al. (2012) showed that the yield difference between organic and conventional cropping systems is more pronounced for cereal crops (excluding maize) than for legumes or perennial crops. Barley grain yield and N uptake obtained in our study were low compared to conventional cropping conditions (Sieling et al. 1998; Kühling et al. 2021). Olesen et al. (2007) and Olesen et al. (2009) demonstrated similar grain yields of spring barley and winter cereal crops under organic farming conditions, respectively, and attributed their results to limited N availability. In maize, high net N mineralization indicates that N was not a growth-limiting factor, which was also shown by Cougnon et al. (2018), who calculated a N fertilizer replacement value > 170 kg N ha^{-1} of grass-clover leys in a study with maize as the following crop. The findings of this study suggest that low net N mineralization and low N fertilization in winter barley resulted in reduced N availability, which caused low grain yields and low N uptake. As differences in SMN content, VWC, and weed growth between mechanical weeding and the chemical control were small, these minor differences did not affect yield and N uptake in harvestable products.

Conclusion

While no effect of mechanical weeding on SMN dynamics was expected in winter barley due to only minor soil disturbance by harrowing and low soil temperatures at the time of mechanical weeding, N mineralization in maize with incorporated grass-clover residues before sowing was also not increased by harrowing and hoeing. As a result, the N uptake of maize remained unaffected by mechanical weeding. However, high net N mineralization in maize was observed, suggesting that any potential impact on soil N dynamics by mechanical weeding may have been masked by previous tillage. Weed pressure was not particularly pronounced in this study, despite higher weed growth in one year and crop after mechanical weeding, and therefore did not result in crop yield losses compared to herbicide application. Furthermore, mechanical weeding resulted in a higher VWC in both crops, which was attributed to increased water infiltration by disrupting the soil crust. This effect may have agronomic significance in terms of efficient water use, whether from rainfall or irrigation, particularly in areas where rainfall events are infrequent due to climate change. Thus, resource use efficiency and yields could be sustained by performing mechanical weeding, while reducing the amount of chemicals applied for weed control into the environment.

Acknowledgements This research was funded by the Ministry of Environment, Energy, and Climate Protection and by the Ministry of Nutrition, Agriculture, and Consumer Protection of Lower Saxony with the support of the Water Management, Coastal Defence and Nature Conservation Agency Lower Saxony (NLWKN) and the Chamber of Agriculture Lower Saxony (LWK). We thank our associated project partners from the cooperation farm D. and W. Bringewatt and E. Nagel for help with laboratory work and the staff members of the experimental farm Waldhof for managing the trials.

Author contributions M.B.: conceptualization, methodology, resources, validation, formal analysis, visualization, writing—original draft/review & editing. I.K.: conceptualization, formal analysis, writing—original draft/review & editing. M.V.: resources, methodology, writing-review & editing. G.B.: supervision, writing—review & editing. D.T.:

conceptualization, funding acquisition, supervision, writing—review & editing.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data Availability No datasets were generated or analysed during the current study.

Declarations

Competing interests 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.

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