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Fresh and degraded maize shoot and root residues temporarily change soil hydraulic properties

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Abstract. Mulching and incorporation of crop residues (CR) into soils are common strategies to sustain soil carbon stocks, return nutrients, and regulate water losses through bare soil evaporation. To date, implementing the effect of mulching strategies into soil-plant-atmosphere models remains challenging due to limited information on their influence on soil hydraulic properties (SHP) as well as on the persistence of these effects over time. We hypothesized that increasing amounts of incorporated maize CR benefits water retention and reduces unsaturated hydraulic conductivity, and that the quality of the CR would determine the persistence of the effects, i.e., that mulching with relatively fast decaying shoot residues would be less persistent than incorporating root residues.

In a laboratory study, we quantified the effect of maize CR in various concentrations (0, 2, and 5 wt.%) on the SHP of a loam soil and additionally measured the SHP of a mulch layer (100 wt.% CR) from saturation to oven dryness. We differentiated between shoot and root CR to quantify the effect of biomass quality and adapted the simplified evaporation method to measure the hydraulic properties of 100% CR layer. The experiments were run in triplicate and repeated after three weeks of incubation under optimal conditions for biological activity (30 °C, 90% RH) to simulate organic matter degradation after harvest. Comparing the SHP before and after incubation provided information about the temporal dynamics of CR effects on SHP.

Compared to the control, water retention increased systematically by 2 to 5 vol.-% across the CR-soil mixtures from saturation to field capacity while the unsaturated hydraulic conductivity was slightly reduced. Incubation reduced carbon mass about 46–50% in 100% CR layers, 7–15% in root-soil mixtures and 21–27% in shoot–soil mixtures, simultaneously altering residue carbon and nitrogen concentrations. Despite this degradation, a positive effect on the soil water retention curve persisted, with water content increasing on average by 1.45 vol.% per gram of carbon per kilogram of soil. However, soil hydraulic properties measured after three weeks showed that much of the beneficial effect had diminished, most notably for shoot residues, which decomposed most rapidly.

Overall, the study demonstrates that the beneficial effects of CR incorporation on the SHP of a loam soil increase with CR amount and persist for at least one month after harvest. In agroecosystems, this post-harvest period and the mulching process are crucial for defining the initial soil conditions for the subsequent crop. Furthermore, the reduced unsaturated hydraulic

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conductivity of the 100% CR layer confirms field observations that mulch layers can effectively reduce water losses through bare soil evaporation.

1 Introduction

The ability of soils to store and conduct water controls many soil functions, from plant productivity and nutrient cycling to groundwater recharge. The relationship between matric potential and water content, the soil water retention curve (SWRC), and the relationship between matric potential and hydraulic conductivity, the soil hydraulic conductivity curve (SHCC), define the hydraulic properties of soils (SHP) and are fundamental for most soil-plant-atmosphere models to describe water flow and transport in unsaturated soils. However, both curves are known to have certain constraints such as in describing drying-wetting processes, hysteresis, spatial heterogeneities or temporal dynamics (Assouline and Or, 2013). For the latter, it is well known that SHP in agricultural soils are not static over time (Strudley et al., 2008), but seasonal dynamics are often neglected because experimental data are missing. In agricultural systems, two typical management operations where we expect significant time dependent dynamics on SHP is the incorporation of crop residues (CR) into soils by tillage practices and the creation of a shallow organic matter layer on the soil surface by mulching straw, sawdust, or leaves (Green et al., 2003; Klopp and Blanco-Canqui, 2022). Both are common approaches to return nutrients, improve soil structural stability, increase soil organic carbon (SOC) contents, and herewith improving SHP (Turmel et al., 2015).

Minasny and McBratney (2018) showed in a meta-analysis the limited effect of SOC on soil available water capacity which was especially true for fine textured soils. The authored summarised that 1% mass increase in SOC on average, increases the water content at saturation, field capacity, wilting point, and plant available water capacity by: 2.95, 1.61, 0.17, and 1.16 mm H_2O 100 mm soil^{-1}, respectively. However, it should be noted that when quantifying the effect of C on SHP in a meta-analysis, C contents are routinely determined for sieved soils < 2 mm where larger plant residues are consequently removed and, thus, the effect of CR might be underestimated. A comparable meta study on unsaturated SHC is, so far, not available. A review paper by Klopp and Blanco-Canqui (2022) investigated the effect of CR on physical soil properties at the field scale and it was summarised that for fields without CR incorporation the saturated hydraulic conductivity of the top 20 cm soil layer was reduced on average from 129 cm day^{-1} to 62 cm day^{-1} and the unsaturated hydraulic conductivity at -0.015 kPa from 1.7 to 1.0 cm day^{-1}. It is noted that the results on unsaturated hydraulic conductivity were based on three field studies and no data were given for dryer conditions. It can be assumed that changes in bulk density (Hohenbrink et al., 2023), reduced wettability and bioclogging (Leuther et al., 2019; Volk et al., 2016), aggregation or a shift in pore size distribution (Rasse et al., 2000; Sindelar et al., 2019) will affect unsaturated hydraulic conductivity, if positively or negatively depends on soil texture. This was also true for water retention at the investigated field sites, where mixed effects (positive, neutral, and negative) of CR removal on the top 10 cm were determined. On average, it reduced the volumetric water content at field capacity from 0.38 cm^3 cm^{-3} to 0.26 cm^3 cm^{-3} and at permanent wilting point from 0.23 cm^3 cm^{-3} to 0.17 cm^3 cm^{-3} which significantly reduced the plant available water capacity by around 0.05 cm^3 cm^{-3} (Klopp and Blanco-Canqui, 2022). The removal of CR in agricultural

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fields does only results in reduced C concentrations but also in a reduction in the abundance of soil macrofauna and other soil engineers (Blanco-Canqui and Lal, 2007; Bottinelli et al., 2015) which will cause feedback to SHP. Thus, it is still unclear to what extent the positive effect on SHP is after incorporation of fresh CR and, further, how long the benefit in SHP lasts in a soil environment with high biological activity. The authors highlight that the effect of CR might change during the season when fresh residues are decomposed over time but that studies are needed to quantify the temporal effect of CR on soil physical properties.

One major reason for the expected temporal dynamics in SHP is that fresh CR in agricultural soils undergo degradation, which alters the physico-chemical properties of soil organic matter (SOM). As a valuable source of carbon and nutrients, CR stimulate soil food-web activity and promote microbial processes within the first weeks after harvest, largely independent of soil type or microbial community composition (Birge et al., 2015). The quality of CR and SOM can cause soil water repellency and hydrophobicity (Miller et al., 2019). Changes in litter quality during decomposition can further regulate decomposition rates and, consequently, the long-term effects on SHP (Córdova et al., 2018). In addition, litter morphology such as tissue density and the formation of pores during decomposition were shown to significantly determine water storage properties of the CR itself (Iqbal et al., 2013). As a result, it was shown that water retention of maize stem residues can also increase with degree of decomposition. Again, while studies on the water retention properties of CR exist, studies on the combined effect of CR incorporation and their biodegradation on both SWRC and SHCC are rare.

In this study we aimed to (i) quantify the extent to which different CR concentration and CR qualities incorporated into a loam soil affect SWRC and SHCC, (ii) to measure the hydraulic properties of pure CR to provide hydraulic properties of a mulching layer, and (iii) to quantify the effect of biological degradation of CR on SWRC and SHCC. In a lab study under constant climatic conditions, the SHP were measured for repacked soil samples with varying maize residue concentrations (0, 2, and 5 wt.%) of two different OC qualities (shoot and roots) from saturation to oven dryness. The experiments were repeated after an incubation time of three weeks to investigate the effect of biodegradation of CR on SHP and thus temporal dynamics we could expect in tilled soil layers. In addition, we measured for the first time water retention and unsaturated hydraulic conductivity of maize CR to provide experimental data to simulate SHP of a mulching layer and root residues in soil-plant-atmosphere models. Changes in CR quality during the experiments were determined by C and N analysis.

We hypothesized that (i) higher CR concentration in loam soil increases soil water retention and decreases unsaturated conductivity compared to soil without crop residue; (ii) microbial degradation processes under controlled climate conditions will diminish the effect of higher concentrations of CR on water retention and hydraulic conductivity within three weeks due to the decay and physico-chemical transformation of the plant material that entails changes in the pore space and wettability; (iii) decomposition rates differ between CR quality, with shoot residues decaying much faster than root residues and thus reducing the effect on SHP after a similar incubation period.

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2 Materials and Methods

2.1 Soil samples and plant cultivation

The soil texture used in this study is classified as loam (World Reference Base) with 33 g 100 g^{-1} sand, 48 g 100 g^{-1} silt, and 9 g 100 g^{-1} clay and which originates from the top 50 cm of a haplic Phaeozem, which was excavated and thoroughly homogenised (Vetterlein et al., 2021). The soil has a pH ($CaCL_2$) of 6.21, and nutrient concentrations of <0.1 g 100 g^{-1} carbonate, 0.084 g 100 g^{-1} total nitrogen (N), and 0.84 g 100 g^{-1} total organic carbon (TOC). For the experiments, the soil was air-dried and sieved to <5 mm.

Maize seeds (Zea mays, Perley, Limagrain GmbH) were first germinated in Petri dishes filled with cotton fibres and tab water. After germination, 30 seedlings were transplanted and cultivated in a fertilized potting compost until flowering (70 - 79 days). Irrigation occurred regularly with fertilized tap water (NPK 4+2+2). After flowering, the plants were harvested and divided into shoot (leaves and stem) and root CR. To remove the plants from the potting compost without destroying the root system, the entire plant-root zone including the surrounding potting compost was lifted from the containers using a small hand shovel and aggregates were carefully removed by hand, shaking, and brushing. The plants were cut in two pieces to separate shoot biomass (leaves and stem) from root biomass. Roots were washed in a 2 mm sieve to clean of any remaining soil particles and stored in a water bath to prevent drying. Both fresh CR (roots and shoot) were cut into pieces of 0.5 cm length and width.

Triplicates of two different treatments of CR (root and shoot) with four different concentrations (0, 2, 5, 100 wt.%) were prepared (Fig. 1). Of each treatment and concentration, 5 g subsamples were stored immediately in a freezer at – 20°C for total Carbon (C) and total Nitrogen (N) analysis. All cylinders were packed according to the same protocol. For the soil-CR mixtures, steel cylinders (250 cm^3, 5 cm in height, 8 cm in diameter) were closed at the bottom with a filter paper and a perforated lid. For each soil-CR mixture replicate, fresh plant residues were mixed with 360 g sieved soil in a container before packing. In intervals, the cylinders were packed with 50 g soil and slightly compacted until a final bulk density of 1.44 g cm^{-3} was reached.

For the 100% CR replicates, a custom-made cylinder was used which had the same outer dimensions as the standard 250 cm^3 cylinder but a smaller volume for the sample. The sample container is made of a PVC block and has an elongated cut-out of 30 cm^3 in the centre. The bottom is closed but has two holes (6 mm in diameter) for the tensiometers and one hole (1.5 mm in diameter) for the temperature sensor. This container enables to use the standard settings of device to measure SHP for a small amount of CR. Once a cylinder was packed, the top was closed using another porous lid and a filter paper.

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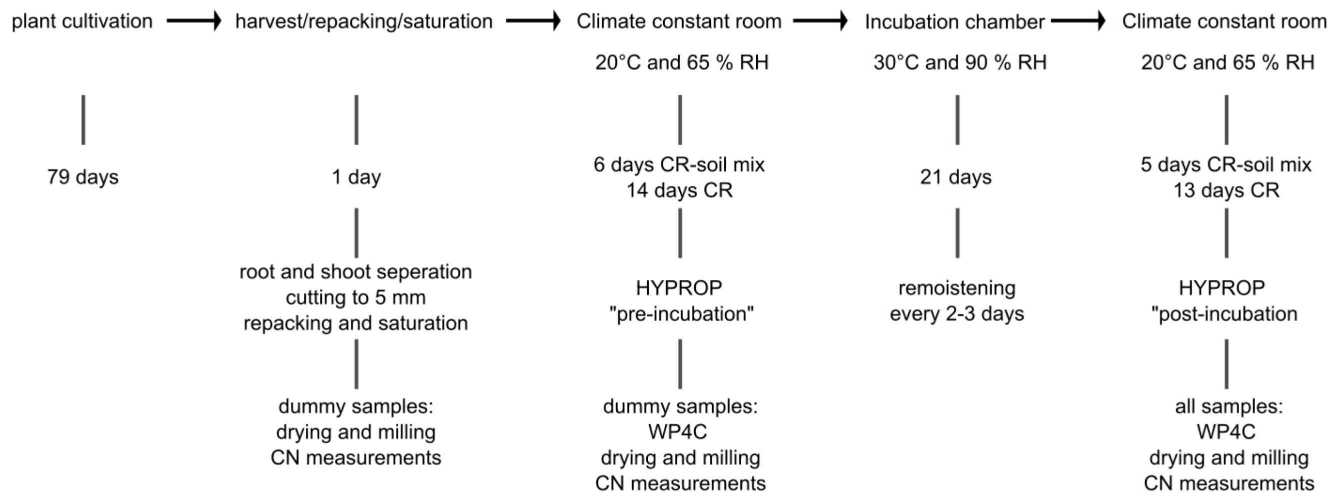

Figure 1 Workflow for the conducted experiments, including the climatic conditions during the measurements and incubation, the days for each processing step, as well as the additional measurements made for each treatment.

Table 1 Sample overview of all tested treatments pre and post incubation. The number of replicates for 100% crop residue samples decreased from pre to post incubation because of biomass losses and space limitations in the incubation chamber.

Fresh biomass concentration [g 100 g^{-1}]	Crop residue	Replicates pre-incubation	Replicates post-incubation	Soil mass (air-dried) [g]	Fresh biomass [g]	Cylinder volume [cm³]	Bulk density (105°C dried) [g cm^{-3}]
0 (control)	-	2	2	360.7	0.0	250	1.39
2	root	3	3	360.7	7.2	250	1.39
2	shoot	3	3	360.7	7.2	250	1.39
5	root	3	3	360.7	18.0	250	1.40
5	shoot	3	3	360.7	18.0	250	1.40
100	root	4	3	0.0	15.0	30	0.057
100	shoot	6	2	0.0	15.0	30	0.083

2.2 Soil hydraulic properties

SWRC and SHCC were measured for all samples using the simplified evaporation method as implemented in the HYPROP device (METER Group, USA). The measurements of the SHP were performed under controlled climatic condition (20 °C, 63 - 67% relative humidity) in a climate constant room since OM degradation was expected to occur during the measurement phase. Before the start of the experiments, the samples were saturated with tab water by capillary rise over night and fully covered for 2 hours to gain near saturated initial conditions but avoiding long periods of anoxic conditions. HYPROP sensor units were prepared following the protocol using degassed water. The HYPROP experiments of the CR-soil mixtures were

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conducted for 9 days until both tensiometer experienced cavitation, and the residual water content was about 20 vol.-%. For each treatment, a dummy sample was run in parallel to take three subsamples at the end of the first round and measure water potential at low water contents via the dewpoint potentiometer WP4C (Meter Group, USA). This is a destructive approach to determine representative water contents and potential, therefore WP4C could not be measured for the same samples that were planned for incubation. After initial saturation, the 100% CR samples contained up to 90 % of water and thus measurements were run for 15 days to capture a wide range in water contents. We stopped the experiments before cavitation because degradation of CR already occurred during the experimental time and some tensiometers loosed hydraulic contact to the CR. Due to biological degradation we measured the water retention characteristics for the first round of HYPROP at dry conditions with WP4C for freshly cut material used to prepare the samples. After the incubation time, the second measurement of SHP followed the protocol of the first round except that after cavitation, three sub samples per CR-soil mixture replicate were taken from the top, centre, and bottom to measure water potential at low water contents via WP4C. Due to the low mass of the 100% CR samples, the entire sample was placed in a WP4C container. All subsamples were measured at various water contents. At the end, all samples and subsamples were dried at 105°C to gain the dry solid mass.

The measured SHP were characterised by fitting the unimodal van Genuchten model (van Genuchten, 1980; Mualem, 1976) as implemented in the Labros SoilView software Version 5.4.0.0 for the soil-CR mixtures and the *SoilHyP* R package (Dettmann, 2018) for the 100% CR samples. The model combines the measurements of the SWRC and SHCC and enables to describe the SHP from saturation to oven dryness:

$$S_e(h) = \left[\frac{1}{1 + (\alpha|h|)^n}\right]^{1-\frac{1}{n}} \tag{1}$$

where α [L^{-1}] and n [-] are shape parameter, h is the matric potential [L], and $S_e(h)$ is the effective saturation (Equ. 2),

$$S_e = \frac{\theta - \theta_r}{\theta_s - \theta_r} \tag{2}$$

θ_s [L^3 L^{-3}] and θ_r [L^3 L^{-3}] are saturated and residual water contents, respectively. The relative hydraulic conductivity function was fitted using the Mualem-van Genuchten function which related the conductivity to the water retention curve (Equ. 3):

$$K(S_e) = K_s\, S_e^{\tau} \left[1 - (1 - S_e^{\frac{n}{n-1}})^{1-\frac{1}{n}}\right]^2 \tag{3}$$

where $K(S_e)$ [LT^{-1}] is the unsaturated hydraulic conductivity, K_s [LT^{-1}] is the saturated hydraulic conductivity, and τ is a dimensionless pore connectivity and tortuosity parameter.

2.4 Incubation experiments, carbon and nitrogen analysis

After the first round of SHP measurements, the samples were covered with a filter paper and a perforated lid, rewetted via capillary rise for 30 min, and the sensor units were carefully removed. The sample bottom was then covered with a perforated lid as well but without a filter paper to promote oxygen supply during the incubation. A climate constant chamber was used for incubation with a constant temperature of 30°C and 10% ventilation leading to a relative humidity of about 90% . Every

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sample experienced in total 3 weeks of incubation time, while every two to three days the sample was weight and rewetted via capillary rise for 30 min to prevent dry spells inside the soil samples but enable oxygen to diffuse.
Total C and N concentrations of each 5 g subsample taken after sample preparation, after first round of SHP measurements (pre-incubation), and after incubation plus second round of HYPROP (post-incubation) were measured by dry combustion using a Elementar C/N Vario Max Analyzer (Analysensysteme GmbH, Germany). This device uses a high temperature combustion method to burn milled sample particles and then analyses the carrier gas for carbon and nitrogen. Each subsample, including the CR, were thawed, air-dried and milled. In contrast to standard protocols for soil samples, the subsamples were not sieved and thus contained all remaining CR.

2.6 Statistics and data management

Data management, data analysis and figures were all carried out using the open-source packages *tidyverse* (Wickham et al., 2019) and *ggplot2* (Wickham, 2016) in R Version 4.1.2 (R Core Team, 2020). The comparison of means for C and N concentration as a function of experimental points in time, i.e. fresh, pre-incubation, and post-incubation, were done using a one-way analysis of variance (ANOVA) for repeated measures in the *rstatix* package (Kassambara, 2020). Due to the low number of technical replicates, we assumed a normal distribution and homogeneity of variance. However, we adjusted the significance level to control for false positives of the pairwise *t-tests* by using the Bonferroni multiple testing correction method. Regressions and correlation coefficients, R^2 and p value, were determined using the *ggpubr* package (Kassambara, 2020).

3 Results

3.1 Crop residue-soil mixtures

The effects of CR incorporation on both SWRC (Fig. 2a) and SHCC (Fig. 2b) were observed across the entire pF range, from saturation to oven dryness. Increasing shoot concentration from 2% to 5% resulted in higher water content at each pF value compared to the control. The effect was mostly pronounced in the wet range of the soil water retention curve (pF 0 – pF 2). Similarly, the increasing root concentration from 2% to 5% also resulted systematically in higher water. With increasing tension, the differences between CR concentration and quality (root and shoot) disappeared. Interestingly, the incorporation of CR reduced the unsaturated hydraulic conductivity around pF 2.5 where the effect on the water retention curve was low. It should be noted that the measurement range of the HYPROP device only covers a part of the conductivity curve.

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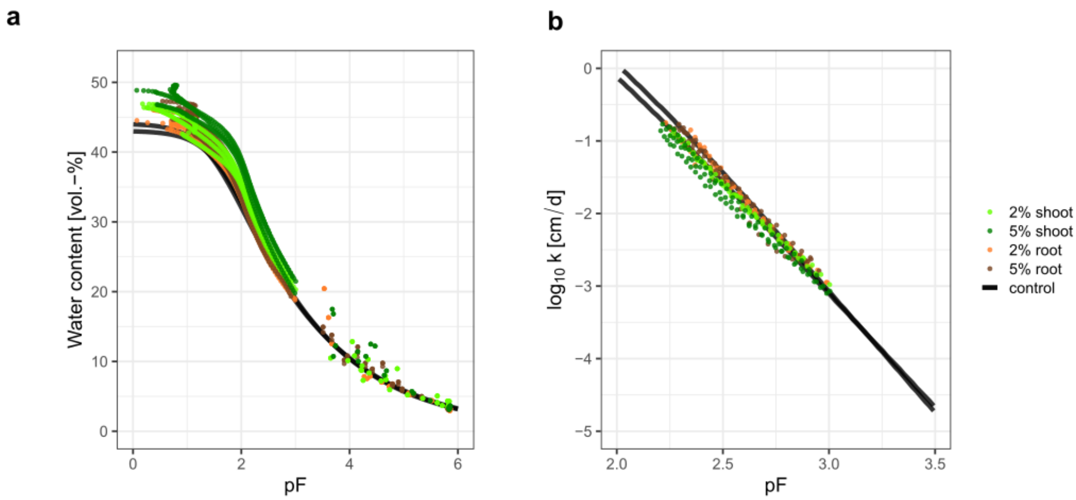

Figure 2 Soil water retention curve (a) and unsaturated hydraulic conductivity curve (b) for crop residues-soil mixtures of different concentrations (control (0% CR addition), 2 wt.% CR, and 5 wt.% CR) of shoot and root residues before the incubation. The results of the control are presented as the fitted vanGenuchten model for better comparision.

The described observations of the measured SHP caused corresponding alterations in the fitting parameters of the unimodal van Genuchten model of the samples pre-incubation (Table 2). The saturated water content (θ_s) increased proportionally with CR concentration by +0.02 cm^3 cm^{-3} (2% shoot and 2% root), by +0.03 cm^3 cm^{-3} (5% root), and by +0.04 cm^3 cm^{-3} (5% shoot), which was also true for the residual water content (θ_r) but to a minor extent. The shape parameter α, which is related to the air entry value of the soil, was decreasing with increasing shoot concentration but was not affected by the root concentration. The shape parameter *n*, which controls the steepness of the water retention curve and where higher values indicate a more abrupt transition from saturated to unsaturated conditions, was increasing with CR concentration for both, shoot and root CR. Both fitting parameter of the SHCC, k_s and τ, have a high uncertainty since measurement points are limited to a certain part of the curve and thus will not be used for interpretation.

Both the SWRC (Fig. 3a) and the SHCC (Fig. 3b) of the control and thus also the fitting parameters were very similar before and after incubation. This was not the case for the CR-soil mixtures. Here, incubation generally reduced the effect of both water retention and, to a minor extent, hydraulic conductivity. Especially the shoot CR-soil samples changed the shape and herewith the shape parameters of the SWRC getting closer to the curve of the control. The effect of incubation on the SHP of root CR-soil mixture samples was comparably low. Interestingly, for all CR-soil mixtures the saturated water content was the same before and after incubation and the reduction in water retention mainly occurred in the pF range from pF 1 to pF 3.

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Table 2 Fitting parameters of the unimodal van Genuchten model pre-incubation and post-incubation. The fitting for each crop residue-soil mixtures is based on all measured replicates. Values in parentheses display the 95 % confidence interval of each fitting parameter.

	control		2% shoot		5% shoot		2% root		5% root	
Parameter	pre	post	pre	post	pre	post	pre	post	pre	post
θ_s [cm³ cm⁻³]	0.436	0.435	0.455	0.455	0.480	0.480	0.454	0.456	0.470	0.471
θ_r [cm³ cm⁻³]	0.000	0.000	0.008	0.004	0.014	0.004	0.003	0.014	0.013	0.010
α [cm⁻¹]	0.025	0.033	0.020	0.038	0.018	0.027	0.026	0.028	0.024	0.030
n [-]	1.258	1.248	1.285	1.244	1.297	1.253	1.272	1.289	1.291	1.279
K_s [cm d⁻¹]	647	1304	150	961	89	180	493	537	440	490
τ [-]	2.7	3.1	1.5	2.0	1.6	0.8	2.0	2.2	2.0	1.6
RMSE θ	<0.01	<0.01	<0.01	0.01	0.01	0.02	0.01	0.01	<0.01	0.01
RMSE log K	0.06	0.1	0.04	0.06	0.09	0.17	0.07	0.07	0.05	0.13

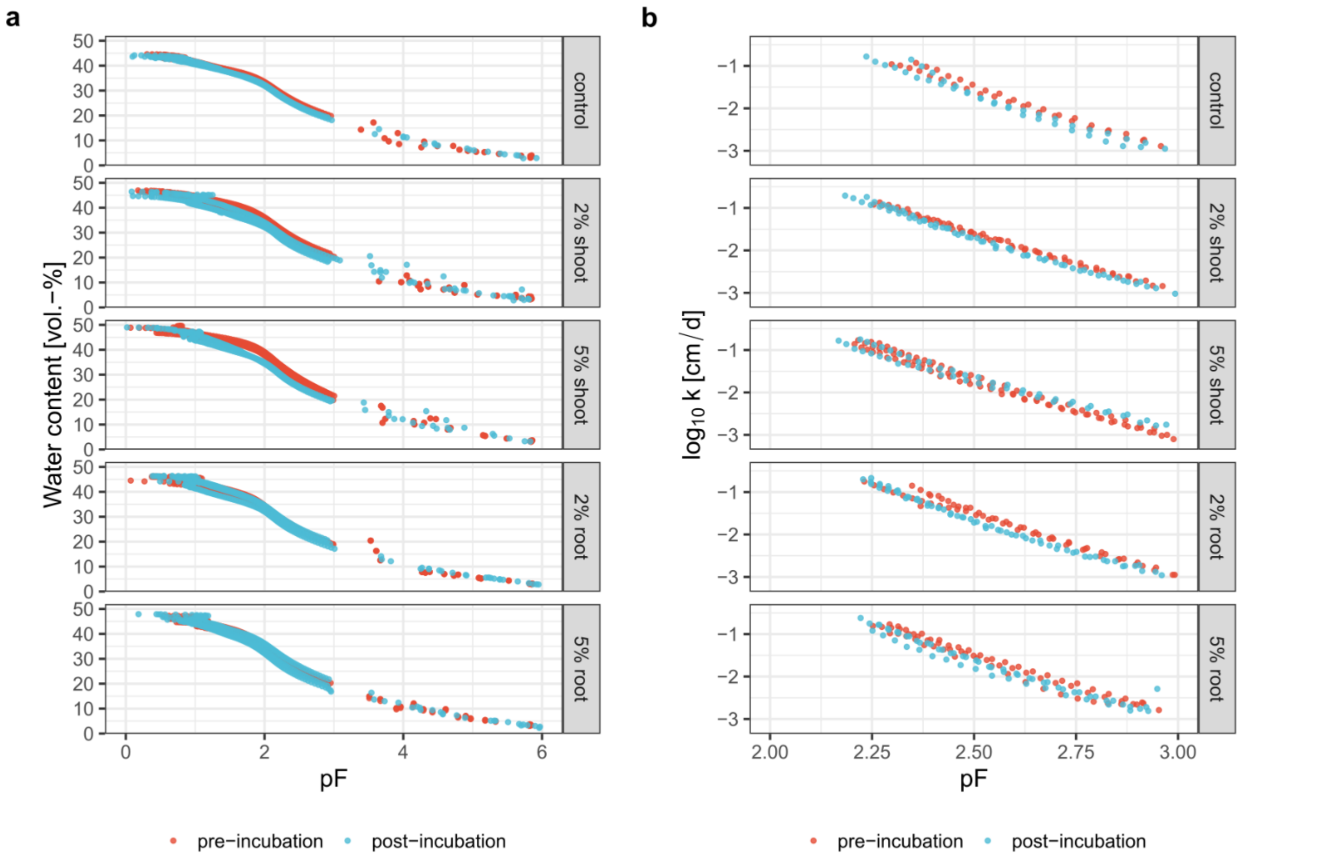

Figure 3 Soil water retention curve (a) and unsaturated hydraulic conductivity curve (b) for crop residues-soil mixtures of different concentrations (control (0% CR), 2 wt.%, and 5 wt.%) of shoot and root residues before (red) and after (blue) incubation.

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3.2 Mulching layer and root residues

Measuring the SWRC and SHCC for 100 wt.% CR with HYPROP provided data mainly from close to saturation (pF 0) to pF 2, while WP4C measurements were done for very dry conditions from pF 5 to pF 6 (Fig. 4). The saturated water content of shoot CR was on average 72 vol.-% and of root CR 77 vol.-% but both showed a high variability compared to the CR-soil mixtures independent of the CR quality. At pF 1.5, the shoot water retention sharply dropped to 34 vol.-% and thus lost around 43 vol.-% of water while root CR lost even around 43 vol.-%. Including both measurements tools, it was possible to describe the data with a unimodal van Genuchten model and fill the gap in data points from pF 2.5 to pF 5. For both CR qualities, the model indicates a significant drop in water retention close to saturation, i.e. water which is drained fast at a low hydraulic head. Differences between the shape parameter α of shoot and root CR pre-incubation indicates that both CR had a low ability to retain water while the shape parameter n, indicates a higher steepness of the SWRC for shoot CR compared to root CR. After drainage of the big pores, the models indicate that shoot residues already reached the residual water content at pF 2, while root residues retained water from pF 2 – pF 4 before reaching residual water content at very dry conditions., Due to the substantial loss of water in the investigated pF range and a low gradient between the tensiometers, measurement points of the SHCC curve were limited to a certain pF range. At pF 2, tensiometers lost contact to the CR and furthermore, the material started to degrade and samples were transferred to the incubation experiment. After incubation, it was observed that the material changed the consistency towards a more biofilm-like substance. However, the degradation of the CR didn't change the SHP very much as shown in Fig. 4a and 4b, as well as by the fitting parameters presented in Table 3. For the shoot residues, note that the reduced number of data points for the SHCC > pF 1 created a high sensitivity of the τ value causing a sharp drop in conductivity which is not supported by data.

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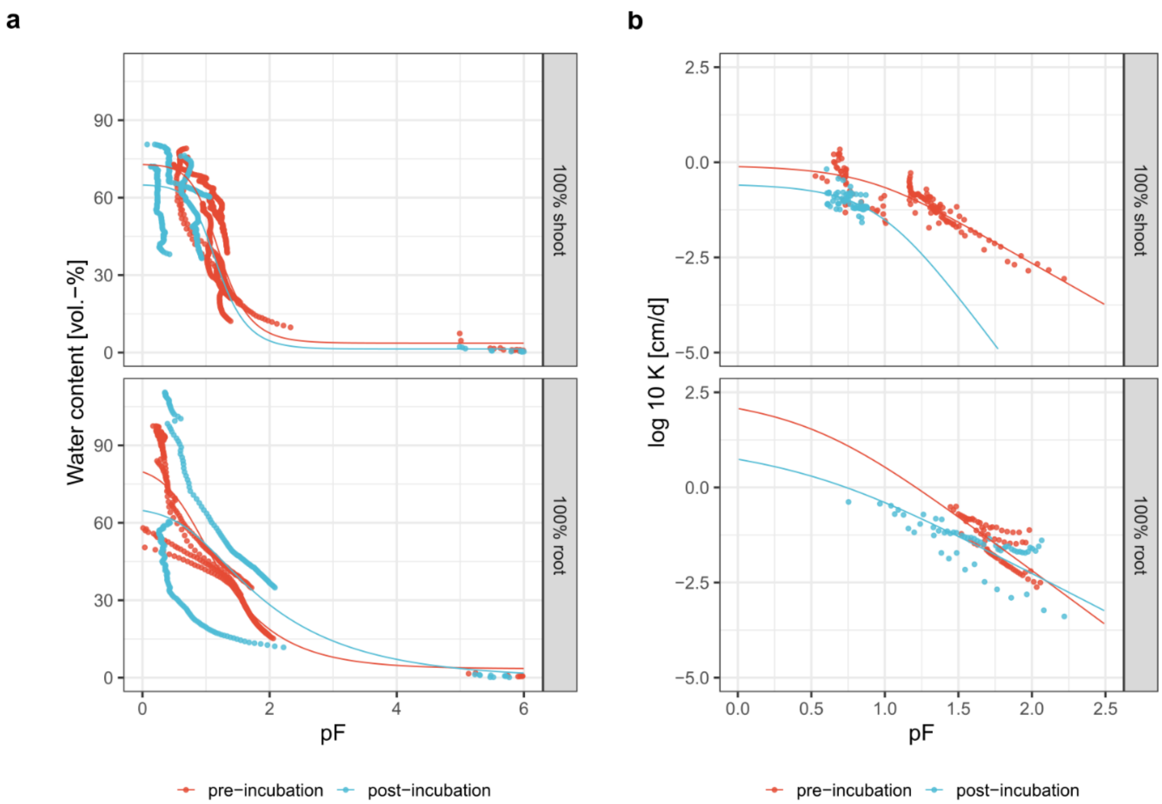

Figure 4 Soil water retention curve (a) and unsaturated hydraulic conductivity curve (b) for 100% crop residue layers of shoot and root residues before (red) and after (blue) incubation. Dots mark the HYPROP and WP4C measurements, the solid lines depict the fitting of the unimodal van Genuchten model.

240 **Table 3 Fitting parameters of the unimodal van Genuchten PDI model after the first round of HYPROP (pre-incubation) and after the second round of HYPROP (post-incubation) measurements for the 100% CR samples. The fitting for each treatment is based on all measured replicates. *marks values were fitting parameters reached model constraints (min/max values).**

	100% shoot		100% root	
Parameter	pre	post	pre	post
θ_s [cm^3 cm^{-3}]	0.729	0.650	0.822	0.661
θ_r [cm^3 cm^{-3}]	0.037	0.013	0.035	0.000
α [cm^{-1}]	0.0889	0.0940	0.217	0.165
n [-]	2.316	2.334	1.532	1.301
K_s [cm d^{-1}]	1	1	361	28
τ [-]	-1.9	0.4	-0.4	-2.0*
RMSE θ	0.11	0.11	0.11	0.23
RMSE log K	0.30	0.08	0.04	0.08

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3.3 Mass losses, Carbon and Nitrogen concentrations as indicators for biodegradation

The total dry mass of fresh shoot (2.5 g) and root residues (1.7 g) decreased during the entire experimental time about 50 % and 27 % (Table 4), respectively, and herewith also changed the dry mass C concentration (fresh shoot 399 g kg^{-1}, fresh root 432 g kg^{-1}, Fig. 5a) , i.e. after the first round of HYPROP (pre-incubation; shoot: 390 g kg^{-1}, root: 376 g kg^{-1}) and after the incubation time and the second round of HYPROP (post-incubation, shoot: 401 g kg^{-1}, root: 350 g kg^{-1}). Consequently, both treatments lost about 50 % of total C. Note that the mass loss of root and shoot CR during the experiments was so severe that for single C and N measurements mass was only sufficient for one measurement without replicates, thus a statistical test was not possible. In contrast to C concentrations, for both CR a significant increase in N concentrations were observed between fresh and pre-incubation, for shoot CR from 12.3 g kg^{-1} to 24.5 g kg^{-1} and for roots from 0.7 g kg^{-1} to 17.9 g kg^{-1} (Fig. 5a). Post-incubation, the N concentration for the shoot CR was decreasing again to 20.0 g kg^{-1} while N concentration for the root CR was about the same 20.6 g kg^{-1}. The initial C/N ratios indicate that shoot CR with C/N ratio of 32.4 were more nitrogen-rich relative to carbon compared to root residues which had a C/N ratio of 61.1. The C/N ratios of both CR decreased mainly at the beginning of the experiment, i.e. shoot CR pre-incubation decreased to a C/N ratio of 15.9 and for root residues to a C/N ratio of 21.0, indicating a biodegradation of CR starting during the first measurement of SHP. Further changes of CR C/N ratio during incubation were comparingly low, which is shown by the post-incubation measurements of shoot C/N ratio of 20.1 and root C/N ratio of 15.7. Interestingly, the change in C/N ratio for shoot CR pre-incubation was also driven by an increase in N concentration.

The incorporation of CR into soil significantly increased the C concentration (p<0.01) of all tested CR-soil mixtures when compared to the control (C 8.3 g kg^{-1}, N 0.8 g kg^{-1}, C/N ratio of 9.6) as well as the N concentration (p<0.05), expect for 2% shoot CR-soil mixture (p=0.46). Compared to the 100% CR samples, the initial C and N concentrations in fresh CR-soil mixtures were by factor 30-36 and 7-16 smaller, respectively, and the observed dynamics in concentrations during the experiment differed significantly. The C concentration of shoot and root CR-soil mixtures were significantly decreasing from fresh (2% shoot: 10.5 g kg^{-1}, 5% shoot: 14.2 g kg^{-1}, 2% root: 11.1 g kg^{-1}, 5% root: 10.2 g kg^{-1}) to pre-incubation (2% shoot: 9.7 g kg^{-1}, 5% shoot: 9.9 g kg^{-1}, 2% root: 9.5 g kg^{-1}, 5% root: 10.5 g kg^{-1}) and further to post-incubation (2% shoot: 8.4 g kg^{-1}, 5% shoot: 10.3 g kg^{-1}, 2% root: 9.4 g kg^{-1}, 5% root: 9.5 g kg^{-1}). The N concentration, however, did not significantly change for all treatments, and thus, the significant decrease in C/N ratio was mainly driven by a decrease in C concentration. As a result at the end of the experiments, i.e. post-incubation, all CR-soil mixtures had a C/N ratio similar to the control (C/N ratio of 9.5). Again, changes in C and N concentrations mainly occurred due to the loss of C (Table 4), which was most pronounced in the shoot treatment were the C mass decreased by 21% for 2% shoot CR-soil mixtures and by 27 % for 5% shoot CR-soil mixtures. For roots CR-soil mixture the decrease was about 7% and 15% for 5% root and 2% root, respectively. Except for 5% root, in all treatments CR degradation occurred already during the pre-incubation measurement.

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Table 4 Total dry mass, Carbon and Nitrogen concentrations and Carbon and Nitrogen mass per treatment. Note that the dry mass estimated for pre-incubated samples is based on one dummy sample per treatment.

	control			2% shoot			5% shoot			2% root			5% root			100% shoot			100% root		
	fresh	pre	post	fresh	pre	post	fresh	pre	post	fresh	pre	post	fresh	pre	post	fresh	pre	post	fresh	pre	post
$mass_{dry}$ [g]	347	347	347	348	348	348	351	349	348	348	348	347	351	348	347	2.5	2.5	1.3	1.7	1.7	1.2
C [g kg^{-1}]	8.3	8.1	8.3	10.5	9.8	8.4	14.2	9.9	10.4	11.1	9.5	9.4	10.2	10.5	9.5	400	390	401	432	376	325
C [g]	2.9	2.8	2.9	3.7	3.4	2.9	5.0	3.5	3.6	3.9	3.3	3.3	3.6	3.7	3.3	1.0	1.0	0.5	0.7	0.6	0.4
N [g kg^{-1}]	0.9	0.8	0.9	0.8	0.9	0.9	1.0	1.1	1.1	1.0	0.8	1.0	1.1	1.1	1.1	12.3	24.5	20.0	7.1	17.9	20.7
N [g]	0.30	0.29	0.30	0.29	0.30	0.32	0.37	0.38	0.38	0.36	0.28	0.35	0.38	0.38	0.37	0.03	0.06	0.03	0.01	0.03	0.02

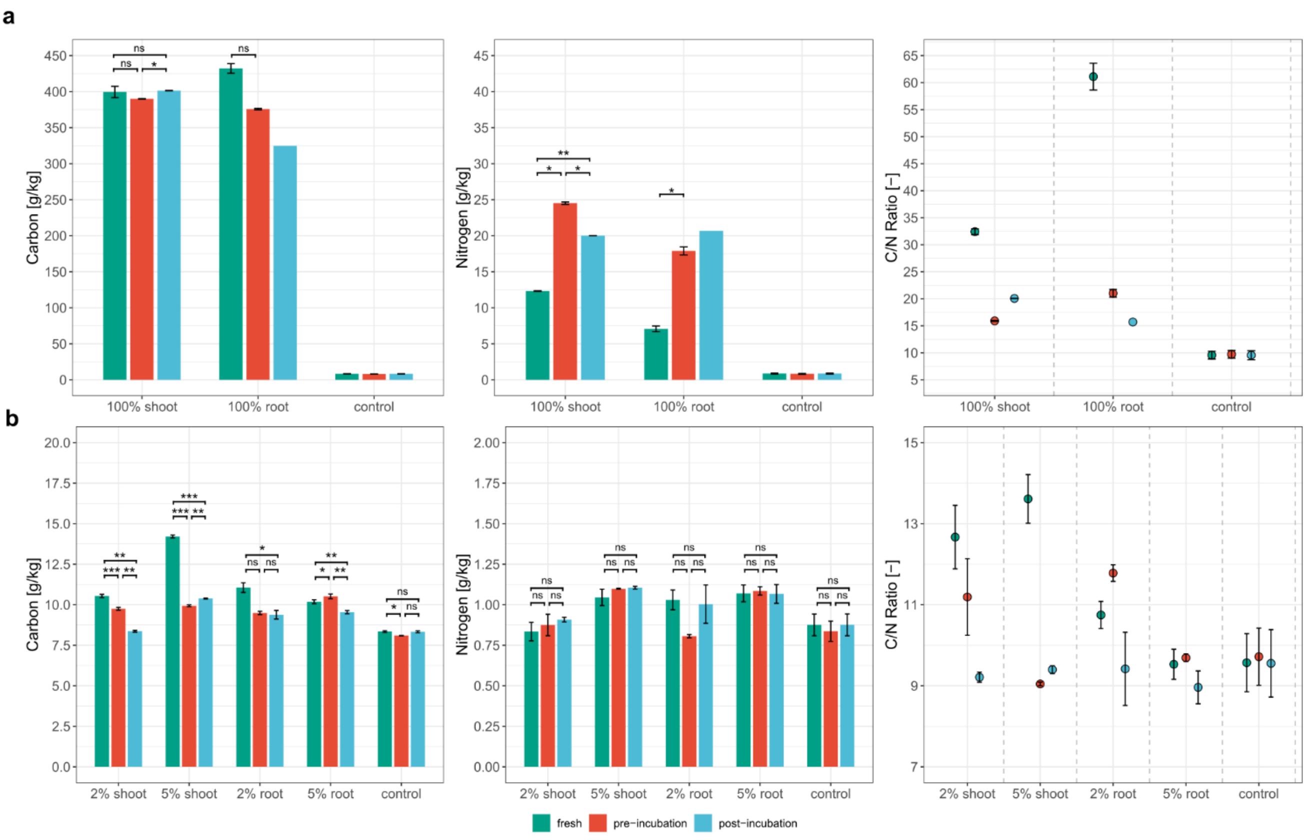

Figure 5 a Carbon concentration, Nitrogen concentration, and Carbon/Nitrogen ratio of the 100% crop residues and crop residue-soil mixtures (b). The error bars show the standard deviation of two technical replicates for the 100% crop residues and three technical replicates for the crop residue-soil mixtures. The level of statistical significance differences between fresh material, pre-incubation, and post-incubatin determined by a *t-test* with Bonferroni correction refers to * = $p < 0.05$, ** = $p < 0.01$, *** = $p < 0.001$. Note, statisitcal significance was not tested for 100% root crop residues post-incubation because of signifcant mass loss leading to a single replicate.

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When correlating the vol.% water content at most common basepoint of the water retention curve, i.e. close to saturation (pF 0), at field capacity (pF 1.8), and at permanent wilting point (pF 4.2), to the samples C concentration (g/kg), it becomes obvious that the positive effect of CR incorporation on water retention is most pronounced in the wet range at pF 0 and pF 1.8 (Fig. 6). The correlations at pre-incubation state were moderate ($R^2 = 0.6$ at pF 0) to weak ($R^2 = 0.4$ at pF 1.8 and pF 4.2) and not statistically significant. However, this was mainly due to the exceptionally high impact of 5 % shoot CR on soil water retention compared to the other treatments. After incubation, there was a strong positive correlation between the water content at pF 0 and 1.8 and the C concentration in the soil, which was mainly due to the decrease in the positive effect of 5% shoot CR. Interestingly, for both basepoints at pre-incubation, the estimated correlation implies an increase of 1.5 vol.-% water content per 1 g C per kg soil. This did not change after incubation for water content at pF 0 and only slightly dropped for water content at pF 1.8. At pF 4.2, the correlation after incubation remained weak, indicating that C concentration had less influence on water retention under high tension (drier conditions). There was no significant correlation between unsaturated hydraulic conductivity and C concentration in the investigated tension range (data not shown)

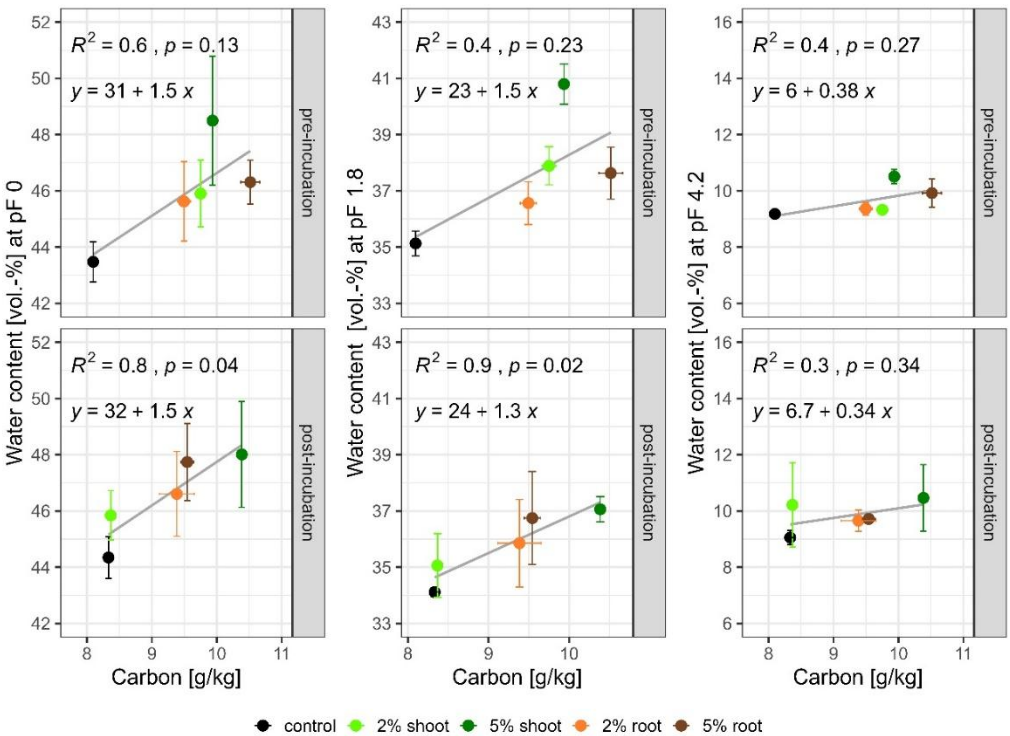

Figure 6 Water content as function of C concentration for most common basepoints of the water retention curve: close to saturation (pF 0), at field capacity (pF 1.8), and at permanent wilting point (pF 4.2) investigated for samples measured before incubation (top) and after incubation (bottom)

4 Discussion

Maize CR have a high surface area and a low tissue density and thus have their own porosity and pore distribution of macro and mesopores which enables retaining a high amount of water (Iqbal et al., 2013). They are composed of hydrophilic compounds, such as cellulose and hemicellulose, and hydrophobic compounds, such as lignin. During the degradation of crop residues, the C/N ratio typically decreases due to preferential microbial consumption of labile carbon fractions (Iqbal et al., 2013). As a result, the relative proportion of recalcitrant, hydrophobic compounds (e.g., lignin-derived aromatics, waxes, and cuticular materials) increases. Consequently, hydrophobicity is expected to increase in parallel with the decline in C/N ratio. At the µm to mm scale, the incorporation of CR can create voids between CR and soils. Biological degradation changes the morphological and chemical characteristics not only of the CR itself but also of the vicinity by stimulating biological growth and nutrient turnover as often observed in the detritusphere (Sanaullah et al., 2011; Védère et al., 2020). These characteristics differ to mineral soil constituents and thus modify the integrated SHP of the CR itself and of CR-soil mixtures. Based on the results of different CR concentration, CR qualities, and biological degradation of CR on SHP of a loam soil it can be summarised that:

i. Incorporating 2% and 5% CR into loam soil significantly increased water retention, particularly in the wet range (pF 0–2) around 2 vol-% to 5 vol-%, and slightly decreased unsaturated hydraulic conductivity around pF 2.5 of about $\log_{10}(-0.05)$ cm d^{-1} for 5% shoot CR.
ii. After three weeks of incubation under controlled climatic conditions, the effects of CR on water retention were similarly high near saturation, but were reduced in the pF range from pF 1 to pF 2.5, and the effect on SHCC was no longer measurable.
iii. The chemical composition of CR significantly changed during the experiment indicating biological degradation of the material. C/N ratios dropped sharply during pre-incubation due to a high C loss for shoot CR and both N increase and C decrease for root CR. The CR-soil mixtures approach control values (~9.5) post-incubation.
iv. Shoot CR decomposed faster than root CR, leading to a more pronounced reduction in soil hydraulic properties post-incubation. Root CR retained its effect on water retention, indicating slower degradation.

These changes in SHP and CR qualities address the hypotheses tested in the study which is discussed in the following.

4.1 The effect of CR concentration on soil hydraulic properties

For fresh CR-soil mixtures, we observed that the saturated water content (θ_s) increased proportionally with CR concentration, while residual water content (θ_r) also rose slightly. The shape parameter α decreased with shoot CR, indicating that CR filled large pores which shifted the air-entry value to higher suctions. The parameter n increased with both shoot and root CR, reflecting a steeper transition from saturated to unsaturated conditions and thus a pore size distribution which is more narrow compared to the control. Both the SWRC and the SHCC of the control and thus also the fitting parameters were highly similar before and after the incubation experiment showing that the experimental setup did not cause hysteresis effects. Various studies

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have demonstrated the positive effect of organic carbon on water capacity (Feifel et al., 2024; Rawls et al., 2003). The controlled laboratory conditions of our studies enabled us to attribute the changes in SHP to the hydraulic properties of CR and its transformation during biodegradation. It is important to note that the reference volume and the mass of soil remained constant across all CR-soil mixture experiments, while we additionally added the CR mass. As a result, we have a greater total mass of solid material in the same volume and thus a decrease in overall porosity, yet a positive effect on the SWRC was measured from saturation to pF 2. The SWRC of the 100 wt% CR samples showed that this was the range in which fresh CR can hold up to 95 vol.% of water. Water retention of shoot CR sharply dropped at pF 2 to 4 vol.%, which is equivalent to pore sizes with a radius of 15 µm, i.e. it can be assumed that majority of shoot CR pore sizes are larger than 15 µm. In contrast, the decline in water retention for root CR was less steep, suggesting that root residues also contain a considerable proportion of pores with radii larger than 1 µm. This interpretation is further supported by the increase in water retention observed at pF 2.5 in the 5% root-CR soil mixture. Overall, the data show that CR can store substantial amounts of water but are only able to retain it against comparatively low matric potentials. These results are consistent with previous findings that reported similar saturated water contents and retention characteristics for maize CR of various sizes (Iqbal et al., 2013). While high residual water contents were measured for fresh CR, a decline was observed due to degradation within 49 days and thus an increase in the pore class radius >29 µm confirming our observations for shoot CR. Similar to Findeling et al. (2007) for rape and rye CR, the 100 w.-% CR samples slightly increased water retention as decomposition proceeded, which the authors attributed to an increase in porosity due to the degradation of the cell walls. Interestingly, fresh CR mixed with soil increased the water absorption capacity of the mineral soil, as they systematically increased the water content at saturation indicating an improved wettability of the soil. However, the increase in saturated water content was again reduced after incubation.

Previous review article reported that for medium textured soils, 10 g kg^{-1} increase in SOC on average, increases the volumetric water content at saturation, field capacity, and wilting point by 3.6, 2.1, and 0.7 mm H_2O 100 mm soil^{-1}, respectively (Minasny and McBratney, 2018). This was similar to the presented results where CR mainly affected the SWRC from saturation to field capacity (here defined at pF 1.8 in the review article at pF 2 and pF 2.5) and only slightly affecting water content at permanent wilting point. Due to the different CR concentrations and CR qualities we covered a range of C contents in soil and estimated that 10 g kg^{-1} increase in soil organic carbon on average, increases the volumetric water content at saturation, field capacity, and wilting point by 1.5, 1.5, and 0.4 mm H_2O 100 mm soil^{-1} for fresh CR, respectively, and by 1.5, 1.3, and 0.3 mm H_2O 100 mm soil^{-1} after three weeks of incubation. The positive effect of mulching and CR incorporation on water retention of loamy soils were reported in field studies (Blanco-Canqui and Lal, 2007; Ramos et al., 2024) and were mostly attributed to the increase in SOC and biological activity. Under field conditions, however, the described positive effect of CR incorporation on water retention might be limited when water contents are fluctuating between field capacity and wilting point.

Falling the described impact of CR on soil SHP, the interpretation of the impact on SHCC is much less straight forward, since the measured data from 100% CR (pF 1 – pF 2) and soil-CR mixtures (pF 2 – pF 3) do not consistently overlap. Based on the fitted van Genuchten model, it can be assumed that the hydraulic conductivity of the soil-CR mixtures close to saturation was by order of magnitude higher as the CR conductivity. Assuming that both root and shoot CR were mainly drained at pF 2 while

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structural pores of the repacked soil are still conducting, air-filled CR might act as physical barriers and thus reduce conductivity. The effect diminished with further drying and the more dominant film and corner flow of the soil matrix. To the best of our knowledge there are no comparable lab studies investigating the effect of CR and its biological degradation on unsaturated hydraulic conductivity. However, previous field studies reported that the removal of CR reduced the saturated and unsaturated hydraulic conductivity under no-till farming (Blanco-Canqui and Lal, 2007) and had mixed effects on both for various farming systems (Klopp and Blanco-Canqui, 2022). Based on our results, it can be assumed that the changes in SHCC often observed in field studies investigating the removal of CR is mainly explained by indirect effects such as the abundance of soil engineers and the creation of a well-connected pore system due to bioturbation rather than due to the CR itself.

4.2 Biological degradation of crop residues significantly reduces the effect on SHP in short time

Plant residues contain populations of bacteria and fungi which are known to colonize the crop and tissues before and after harvest. These microorganisms are able to decompose readily available substrates and change herewith the chemistry of CR and morphology of cell walls (Machinet et al., 2009). The decomposition of maize CR is highly time-dependent and occurs more rapidly in the early stages of decomposition. Depending on the litter quality, often classified by the C/N ratio, both tested maize CR root and shoot can be considered as CR of lower quality compared to other CR (Córdova et al., 2018; Elias et al., 2024), with fresh shoot CR (C/N ratio of 32.4) being more nitrogen-rich relative to carbon compared to root residues (C/N ratio of 61.1). Incubation studies have shown that after 46 days of incubation most of the litter-C remained as residual litter (Córdova et al., 2018), which was especially true for low-quality litter from maize (79 – 85 %), with high carbon/nitrogen (C/N)-ratios and high lignin contents, but also for high-quality litter such as oats (61 – 69 %) or alfalfa (67 – 72 %). In another incubation study, Elias et al. (2024) showed that more high-quality litter-C was respired relative to low-quality litter across different mineral compositions and that more litter-C was found as particulate organic matter and as stabilised, mineral-associated organic matter from low quality OM. In mixtures with minerals, 25 % of litter-derived C can be respired within days and after that respiration rates slow down (Elias et al., 2024), which was similar to the C losses we determined for shoot CR- soil mixtures (21 – 27%). The C loss from root-CR was comparably lower (7 -15%). In soil mixtures under comparable conditions (25°C), maize stem residues decreased their C content from 464 g kg^{-1} dry mass to 452 g kg^{-1} dry mass while increasing the N content from 2.9 g kg^{-1} dry mass to 7.4 g kg^{-1} dry mass within 49 days of incubation, reducing the C/N ratio from 160 to 61 (Iqbal et al., 2013). Interestingly, the authors measured a reduction in soluble C fractions, little changes in hemicellulose and cellulose content while the content in Lignin increased, i.e. the relative content of hydrophobic substances increased. This might be one reason for the observed changes in unsaturated hydraulic conductivity and why carbon-rich amendments improved the soil's ability to retain water at low to moderate tensions but not at high tensions when hydrophobicity can become a dominant factor. It also confirms our observations, that biological degradation of CR already occurred during the first measurements of SHP and continued during incubation. Interestingly the effect of biological degradation during the incubation period on SHP was still significant and thus might have even been bigger when conducting the post-incubation HYPROP experiments under less ideal conditions. The decision of conducting the SHP measurements at 20°C was made up on two (i) simulating more realistic conditions comparable to a topsoil after harvest in Juli – September, and (ii) the technical fact that the measurement time of SHP would have been much longer at cold temperature at reduced respiration rates which might have had resulted in similar biodegradation.

5 Conclusion

In this study we investigated the effect of fresh and degraded root and shoot maize CR on SHP and it can be concluded that (i) higher CR concentration in loam soil increased soil water retention and decreases unsaturated conductivity compared to soil without crop residue; (ii) for unsaturated conditions the microbial degradation processes under controlled climate conditions diminishes the effect of higher concentrations of CR on water retention and hydraulic conductivity within three weeks due to the decay of the plant material that entails changes in the pore space; (iii) decomposition rates differ between CR quality, with shoot residues decaying much faster than root residues and thus reducing the effect on SHP after a similar incubation period; (iv) for both CR, C loss and changes in C/N ratios indicate an increase in relative proportion of recalcitrant, hydrophobic compounds. These findings are significant to understand temporal changes in SHP of topsoils often observed after harvest, which was simulated by the root decay, or after CR incorporation by tillage, which was simulated by root and shoot decay. Furthermore, the study provides a set of SHP which can be used to simulate water flow of root and litter residues on the pore to sample scale and enables to consider the effect of fresh and degraded mulch layers in soil-plant-atmosphere models. Since the effect of CR on SHP could not only be explained by chemical changes but also due to morphological characteristics a combined study including the monitoring of structural changes by X-ray Computed tomography could give further insides to the effect of fresh and degraded maize shoot and root residues on soil hydraulic properties.

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Data availability

The source data underlying Fig. 1 – 5 and Table 1 – 4 are provided in this paper. In addition, the data set is archived and provided by the University of Bayreuth's Institutional Respository for Digital Research Data https://doi.org/10.57880/rdspace-ubt-52 (Leuther, 2026).

CRediT authorship contribution statement

Frederic Leuther: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Alina Langanki**: Visualization, Investigation, Formal analysis, Data curation. **Eva Lehndorff**: Writing – review & editing, Supervision, Conceptualization. **Efstathios Diamantopoulos**: Writing – review & editing, Supervision, Project administration, Methodology, Funding acquisition, Conceptualization

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Competing Interest

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

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