



The Impact of Poplar Short Rotation Coppice on Topsoil Physical Properties and Related Water Conditions

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Abstract

In Europe, the establishment of short rotation coppice (SRC) systems for biomass production has been expanding in the last decades. Several studies have considered the impacts of SRC on soil properties; many have focused on studying its effect on biochemical properties while only a few have addressed physical and hydraulic properties. This study reports the assessment of soil physical and hydraulic properties on two SRC sites on sandy soils planted with 3-year-old poplar trees and an adjacent conventional agricultural field in Western Slovakia. All sites contain a comparable sandy loam soil texture and both SRC fields differed only in the groundwater accessibility. Water infiltration experiments were conducted in the field with subsequent sampling of the upper topsoil (0–5 cm depth). The samples were further processed in the laboratory to obtain the water retention and hydraulic conductivity functions of the soil covering a wide range of soil pore saturation. These hydraulic functions were fitted by using the bimodal version of Kosugi-Mualem's hydraulic model to estimate the pore-size distribution (PSD) of the soils. The comparison between the SRC field neighboring the agricultural field and the latter showed similar hydraulic soil properties such as the topsoil water retention. However, macropore content, bulk density (BD) and infiltration capacity differed under SRC particularly in the tree row. Analogously, the two SRC fields showed similar topsoil water contents. Other soil properties differed presenting an increased macropore content and higher BD in the SRC field with distant groundwater connection. Our findings suggest that the SRC management may influence the topsoil properties.

Keywords Short rotation coppice (SRC) · topsoil properties · pore-size distribution · Kosugi-Mualem model

Introduction

Poplar plantations for bioenergy or dendromass production have been expanding in Europe in the last decades. This development has been largely supported by policy makers under the framework of the EU Biomass Action Plan and the Renewable Energy Directive [1] since products derived from agriculture and forestry play a key role to mitigate climate change and to secure energy supply.

Increasing biomass production led to growing implementation of SRC systems which particularly on former agricultural fields show promising yield developments [2]. The rapid

establishment of plantations implies a substantial change in the management practices which may have consequences on soil and water resources.

The impacts of SRC on water resources have been widely studied [3–7]. Soil-related investigations have mainly focused on the impacts of SRC on soil ecology [8–13], whereas changes on soil physical properties have been poorly studied. Evaluations of soil properties mainly occurred as part of an assessment of site characteristics affecting SRC size, quality and sustainability of yields [14, 15].

For a sustainable management of SRC plantations, the water availability in the soil needs to be considered. Soil hydraulic properties such as water storage depend on soil structure, and on soil hydraulic properties, both are affected by land use and land management which dynamically change over the course of the season [13, 14, 16, 17]. The impact of SRC on soil hydraulic properties can be determined by relating the water retention and hydraulic conductivity functions through hydraulic functions [17] using a combination of field and laboratory experiments. For example, the application of the

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bimodal version of Kosugi-Mualem's model has shown that it is possible to assess the impact of land management change on the pore-size distribution of the soil [17–19].

These methods have been found reliable to study the effects of machinery work on soil properties in agricultural fields. Kreiselmeyer et al. [20] state that the goodness of fit between field and laboratory measurements improves with the application of the bimodal version of Kosugi's model predicting an appropriate representation of the hydraulic functions.

Despite its importance, only few studies have concentrated on the effects of SRC on the soil PSD and focussed on macroporosity [20], which is mainly attributed to root growth. Likewise, research related to changes of soil physical properties such as BD or infiltration capacity in the period after the establishment of SRC has been poorly done. Makeschin [15] found an increased BD due to natural compaction after site preparation. Kahle and Janssen [20] reported reduced BD in the top 10 cm by comparing a SRC plantation and an adjacent agricultural land. To date, the understanding related to the effects of management operations in SRC on soil hydraulic properties within the plantation sites itself is insufficient.

In the presented study, we determined the impact of SRC management on soil physical properties. We did infiltration experiments with subsequent sampling of the upper topsoil. Two sites with 3-year-old SRC poplar hybrid clones differing only in their accessibility to groundwater were selected. As a control, one adjacent agricultural site with comparable soil properties was chosen. Regarding soil texture, all sites were similar and dominated by sand.

The objectives of this study were to (1) evaluate the impact of SRC on the topsoil hydraulic properties (water storage infiltration capacity and PSD) in contrast to an adjacent agricultural field and (2) to analyse the effect on SRC topsoil properties brought by different groundwater accessibility. We hypothesize that there are differences in soil hydraulic properties and PSD between the agricultural site and the SRC. Furthermore, we expect to see differences in the topsoil properties between SRC systems with different groundwater connection.

Materials and Methods

Study Site and Sampling Design

The present study took place in the Skalica area in western Slovakia characterized by a European continental warm and temperate climate. The mean annual precipitation is 518 mm with minimum and maximum precipitation occurring in February and June respectively (1982–2012, data obtained from climate-data.org). The coldest month in the year is January and the warmest month is July. The temperature

ranges from -5 to 25 °C and the topography is predominantly plane with no slopes.

Our assessment involved field experiments and sampling to measure soil hydraulic properties. The experiments were performed on three adjacent sites (Fig. 1): two under poplar SRC sites, with statistically different groundwater accessibility ($p < 0.05$), SRC-D (D stands for distant groundwater access) and SRC-N (N stands for near groundwater access) and one agricultural land. The overall soil texture in all fields is classified as a sandy loam [21].

SRC sites and the agricultural field differ in their land management. On the one hand, the agricultural field is subjected to more intense practices within a year, such as machinery work for seeding, harvesting and specific weed and pest control. On the other hand, SRC fields after the tree planting weed control have been done once a year and no fertilizers have been applied. SRC fields are historical agricultural sites which have been converted to marginal lands until the establishment of SRC. In the agricultural field, the crop rotation comprised winter wheat, sunflower and corn. At time of sampling, the agricultural field was planted with winter wheat.

At the beginning of our study, the poplars in both SRC fields were growing in their third year which represents the early stage of the SRC after its establishment. The tree diameter at breast height (DBH) was measured in a total of 21 and 20 trees in field SRC-N and SRC-D, respectively, presenting the former one a smaller range of values. Tree height was measured and average values were visibly smaller in field SRC-D. Data for DBH of both sites is given in Table 1.

Sampling and Analysis for Soil Hydraulic Properties

Sampling was conducted in the end of March 2019. Since variations in soil structure are expected to be larger in the topsoil [22], we collected undisturbed soil cores (250 cm^3) from a depth of 0 to 5 cm. Undisturbed samples were taken, four in the agricultural site and nine in each SRC sites, by thoroughly removing the litter layer and small herbaceous vegetation.

In each SRC, the samples were taken in different sub-areas: the tree row, the wheel lane and the middle lane (Fig. 1). In the tree lane, the samples were taken exactly in the middle between trees (separated by 1.5 m) and between consecutive trees. The samples from the wheel lane were around 1 m distant from the tree lane and the middle lane. In the agricultural field, samples were taken sequentially in line. Distance between the sampling points was 1 m for a total line length of 5 m distant from the site edges to avoid additional compaction.

Additional to the soil cores, disturbed samples were taken. They were air-dried and divided into sub-samples for the analysis of texture and total C and N. For the CN analysis, sub-samples were ground and measured with the Vario TOCTM cube (Elementar, Hanau, Germany). As there was no

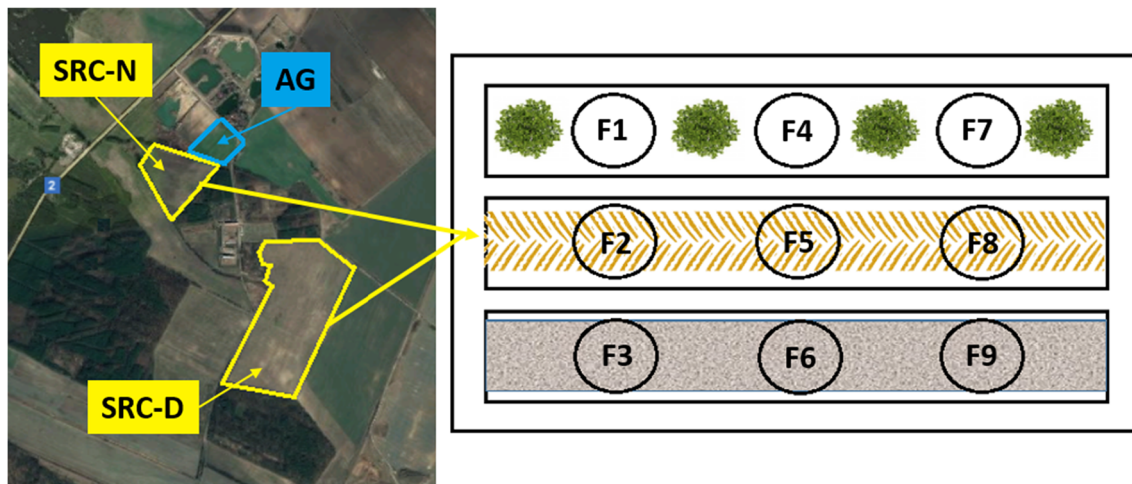


Fig. 1 SRC sites and agricultural field boundaries and locations. The sampling design in each SRC field considers three sub-areas with three repetitions. The considered sub-areas are the poplar tree row—PL (F1, F4, F7); the wheel lane—WL (F2, F5, F8); and the middle lane—ML (F3, F6, F9)

carbonate present in the soil, total C content can be assumed to represent organic C. Independent sub-samples were used to determine the soil texture by combined sieving and sedimentation analysis. Before analysis, organic matter was removed with the addition of hydrogen peroxide and particles have been dispersed by the addition of sodium diphosphate.

Prior to the collection of the undisturbed samples, infiltration in the topsoil was measured with a hood infiltrometer [23]. The data from the infiltration experiments were evaluated according to Kreiselmeyer et al. [17].

For the determination of the water retention and hydraulic conductivity characteristics, the HYPROP® device (METER Group Inc.) was used. This device works under the Schindler’s simplified evaporation method [24], based on the Wind’s approach [25] which yielded reliable results [26]. The HYPROP® system comprises a sensor with two tensio

shafts which were carefully inserted in the soil samples. These sensors are positioned at different depths (1.25 and 3.75 cm) [27]. They are able to record the pressure within the soil at 10–15-min intervals until the air entry point of one of the tensio shafts is reached (after 6–7 days) [26, 27]. The whole system was positioned in a scale to record the weight variations in the sample due to water evaporation.

At the end of the evaporation experiment, the samples were carefully sieved (2-mm sieve), where it was evident that the overall samples from field SRC-D showed a high content of roots in comparison to SRC-N and the agricultural field. From the sieved material sub-samples, 30–40 mL was taken to proceed with the determination of the permanent wilting point (PWP) which was determined in the laboratory by means of the ceramic pressure plates. The sub-samples were placed in small rings and positioned directly in contact with the

Table 1 Summary of field characteristics. Field A: agricultural field. Fields SRC-D and SRC-N: SRC sites

Subject	Field A	Field SRC-N	Field SRC-D
Field coordinates	48° 46' 9.08" N 17° 5' 49.41" E	48° 46' 9.08" N 17° 5' 49.41" E	48° 45' 51.90" N 17° 6' 28.80" E
Current crop	Winter wheat	Hybrid poplar	Hybrid poplar
Sand [Mass-%]	75.9	72.3	83.7
Silt [Mass-%]	15.1	16.6	11.9
Clay [Mass-%]	9.0	11.1	4.4
Main texture group (*)	Loamy sand	Loamy sand	Loamy sand
Total C [mass%]	1.09	2.01	0.41
Total N [mass%]	0.11	0.20	0.04
Mean groundwater below surface [m]	1.8	1.8	3.1
Poplar mean DBH [cm] (**)	-	9.5	5.5
Poplar mean height [m] (***)	-	6.8	3.3

*Soil texture classes according to German Classification (Bodenkundliche Kartieranleitung, 2005). **DBH, diameter at breast height. ***Ökoforestino survey 2017–2018

previously fully saturated ceramic plate inside the pressure chamber. The container was pressurized at 15 bar until no more water was extracted from inside (5–6 days). The remaining soil from the sieving was oven-dried (105 °C, 24 h) to calculate the remaining water content (θ_r) and BD (particle density assumed as 2.65 g cm⁻³).

To process the results obtained from the abovementioned devices, the software HYPROP-Fit [28] was employed. The predictive model selected in the software on the basis of an appropriate representation of the curves was the bimodal version of the Kosugi's [29] and Mualem's [19] model which is based on the assumption of a lognormal distribution of the soil PSD [30]. The Kosugi bimodal model was selected in accordance with Kreiselmeier et al. [22], since it is able to represent the structural and textural domains of the pore-size distribution. The parameters of this model have a physical meaning; therefore, it is adequate to assess the soil physical properties through its PSD [31].

The water retention and the hydraulic conductivity functions by Kosugi-Mualem's model are given by Eqs. 1 and 2, respectively. The bimodality of the curve is identified by $k = 2$ and both sub-curves are determined by $i = 1$ and $i = 2$, structural and textural domains respectively.

$$S_e(h) = \frac{\theta - \theta_r}{\theta_s - \theta_r} = \sum_{i=1}^k w_i \left\{ \frac{1}{2} \operatorname{erfc} \left[\frac{\ln \frac{h}{h_{mi}}}{\sqrt{2}\sigma_i} \right] \right\} \quad (1)$$

S_e (-) represents the effective saturation as a function of the pressure head h (cm). Parameters θ , θ_s and θ_r (cm³ cm⁻³) are the volumetric saturated and residual water content respectively, w_i (-) is a weighing factor for each sub-curve ($0 \leq w_i \leq 1$; $\sum w_i = 1$), erfc is the complementary error function, h_{mi} (cm) is the median pressure head at which the effective saturation of the respective sub-curve $S_{ei}(h_{mi}) = 0.5$, and σ_i (-) is the standard deviation of the lognormal soil pore radius defining the width of the PSD.

$$K(h) = K_{sat} \frac{S_e^{0.5}}{4 \left[\sum_{i=1}^k \frac{w_i}{h_{mi}} \exp \frac{\sigma_i^2}{2} \right]^2} \left\{ \sum_{i=1}^k \frac{w_i}{h_{mi}} \exp \frac{\sigma_i^2}{2} \operatorname{erfc} \left[\frac{\sigma_i}{\sqrt{2}} \operatorname{erfc}^{-1} 2S_{ei} \right] \right\}^2 \quad (2)$$

From the hydraulic function parameterization, Kosugi-Mualem's model provides relevant parameters to assess the PSD of the soil since it represents the relative abundance of each pore size in a representative volume of soil [29, 32]. Such parameters are $h_{m1,2}$; $\sigma_{1,2}$; $w_{1,2}$; θ_r ; θ_s ; and $r_{m1,2}$, where the last one corresponds to the median pore radius derived from h_{mi} through the Young-Laplace equation ($r_{mi} = 0.149 \text{ cm}^2/h_{mi}$ [31]). The PSD of the soil can be estimated by applying Eq. 3 [15]. It calculates the volume fraction taken up by different pore size classification, involving the parameter Φ which represents the porosity defined as $\theta_s - \theta_r$.

$$g(r) = \sum_{i=1}^k w_i \frac{\Phi}{\sqrt{2\pi}\sigma_i r} \exp \left[-\frac{\ln \frac{r^2}{r_{mi}^2}}{2\sigma_i^2} \right] \quad (3)$$

We used the pore-size category classification by Brewer [33]. It covers a wide range of radius divided in three major classes (with r = pore radius): micropores ($5 > r > 30 \text{ }\mu\text{m}$), mesopores ($30 > r > 75 \text{ }\mu\text{m}$) and macropores ($r > 75 \text{ }\mu\text{m}$).

Results

Soil Texture, C and N Contents and Soil Bulk Density

Soil texture and total C and N contents found in the topsoil of all analysed fields are presented in Table 1. The highest total C and N contents were found in SRC-N. In contrast, these parameters were reduced to half in the agricultural field. The dominating soil particle-size fraction found in all fields was sand. The highest content of sand was found in SRC-D, whereas field SRC-N presented the highest silt and clay contents.

The BD found in SRC-N (mean 1.27 g cm⁻³) was similar to the agricultural field (mean 1.30 g cm⁻³), both classified as low values [21] (Fig. 2). Field SRC-D showed BD variations when compared to SRC-N (Fig. 2). The average BD in field SRC-D (1.47 g cm⁻³) was 15% higher. The most prominent variation was seen in the wheel lane, presenting values ranging from 1.25 up to 1.49 g cm⁻³.

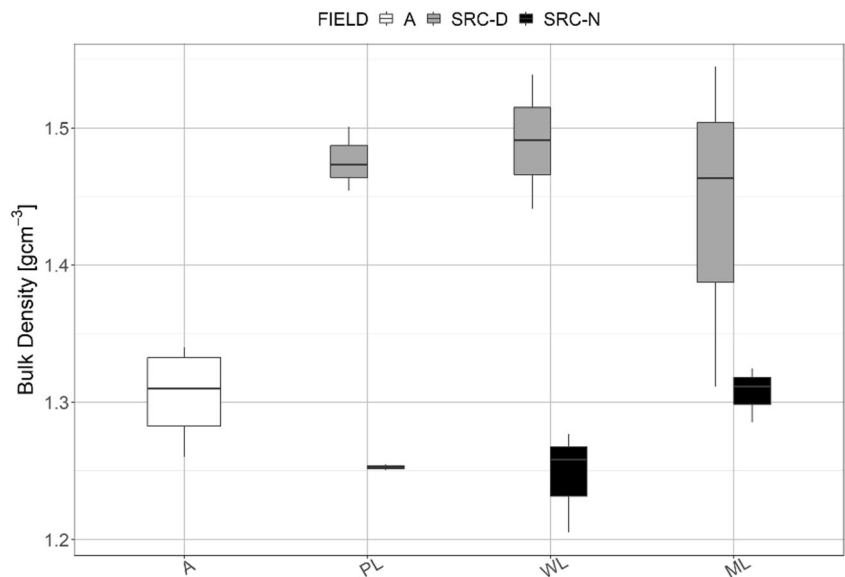
Infiltration Capacity and Water Retention

The mean infiltration capacity determined with the hood infiltrometer in the different areas within field SRC-N ranged from 1.68 to 2.62 log₁₀ cm d⁻¹ where the highest values were found in the tree line and the lowest in the middle lane (Fig. 3). In the case of SRC-D, the highest infiltration capacity was found in the poplar and the middle lane (2.41 and 2.45 log₁₀ cm d⁻¹ correspondingly), whereas the lowest was in the wheeled area (1.64 log₁₀ cm d⁻¹). The overall infiltration capacity seen in the SRC fields exhibited comparable values in contrast to the mean value found in the agricultural field of 2.34 log₁₀ cm d⁻¹. Comparing the two SRC fields, only the tree rows presented similar infiltration capacity values (Fig. 3), showing a high spatial variability.

The different sub-areas in SRC-N showed comparable water contents at field capacity (FC) and plant available water (PAW) (Fig. 4). On average, the water contents at such stages were 24.1 vol% and 17.6 vol% accordingly, representing lower values when compared to the agricultural field.

The water content at FC in field SRC-D showed lower values, on average 16 vol% of the topsoil, in contrast to

Fig. 2 Comparison of bulk density (BD) in the topsoil samples between the agricultural field (A) and both SRC fields (SRC-D and SRC-N). The BD values are presented according to the different analysed areas: (A) agricultural practices, (PL) poplar tree row, (WL) wheel lane and (ML) middle lane



SRC-N (Fig. 4). However, the average water content at PAW showed only a 4.5 % variation between both SRC fields.

Porosity and Pore-Size Distribution

Mean total porosity between SRC fields and the agricultural field was comparable, ranging from 44 to 59 vol% (Fig. 4). However, some sub-areas in the SRC fields presented a slightly higher porosity than the agricultural field. Such results were seen in the tree row in both SRC fields and particularly in the middle line in SRC-D, which presented the highest porosity.

Figure 5 shows the PSD of the topsoil, calculated using the parameters from Kosugi-Mualem’s fitting in Eq. 3. Results demonstrate that in the agricultural field, the micropore content (59 %) dominated over the macro-meso pore fraction (41%). Field SRC-N showed an overall increased macropore

content in comparison to the agricultural field. Such results point to an enhanced infiltration of water in the upper soil layer in this sub-area, evidenced by the infiltration capacity measurements. The pore variation within field SRC-N was largest in the tree row, presenting a 19% higher total macropore fraction and accordingly reduction of micropore content (Fig. 5). In contrast, the wheeled sub-area presented higher micropore fractions, which was comparable to the one found in the middle lane and the agricultural field. Similarly to our results, Kahle and Janssen [34] found that the first 20 cm soil layer in a SRC plantation had higher total porosity than under cropland. Unlike results from SRC-N and the agricultural field, SRC-D exhibited a larger volume of macropores (Fig. 5). Surprisingly, the average macro- and mesopore contents in this field were 16% and 42% higher, respectively, having consequently a 58% micropore reduction.

Fig. 3 Comparison of infiltration capacity in the topsoil samples between the agricultural field (A) and both SRC fields (SRC-D and SRC-N). Results are presented according to the different analysed areas: (A) agricultural practices, (PL) poplar tree row, (WL) wheeled lane and (ML) middle lane

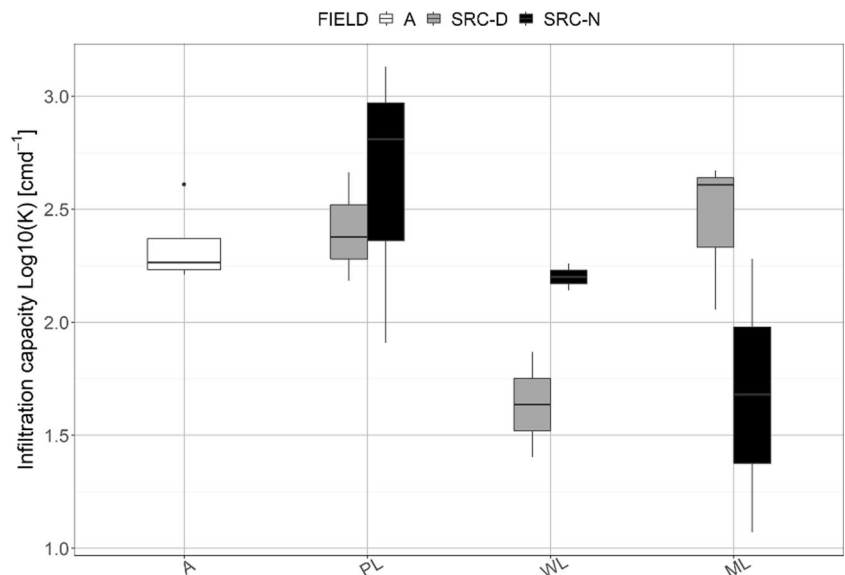
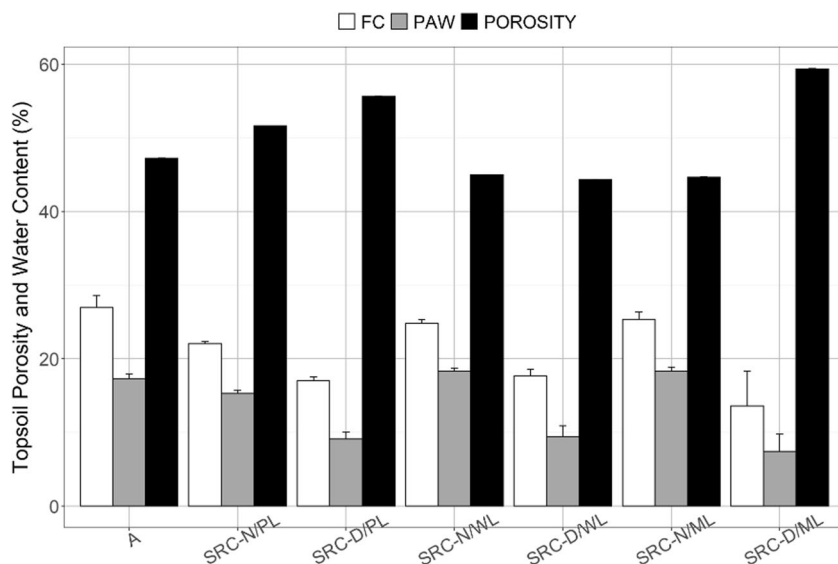


Fig. 4 Comparison of topsoil water content at field capacity (FC), the plant available water (PAW), and the total porosity between agricultural field (A) and both SRC fields (SRC-D and SRC-N). Values from each analysed sub-area within the SRC fields are depicted: (PL) poplar tree row, (WL) wheeled lane and (ML) middle lane



Discussion

Influence of SRC on Total Soil CN and BD

Previous studies reported that SRC plantations have a high input of C in the topsoil, developing biological and soil fauna

activity [11]. For example, Dong et al. [35] found higher litter deposition under SRC in comparison to abandoned lands, increasing the C content in the topsoil even at early stages of the plantation (0.5–5 years). Similarly, Kahle et al. [36] found increased total C and N contents in a 12-year-old poplar SRC in contrast to a former agricultural land, which was

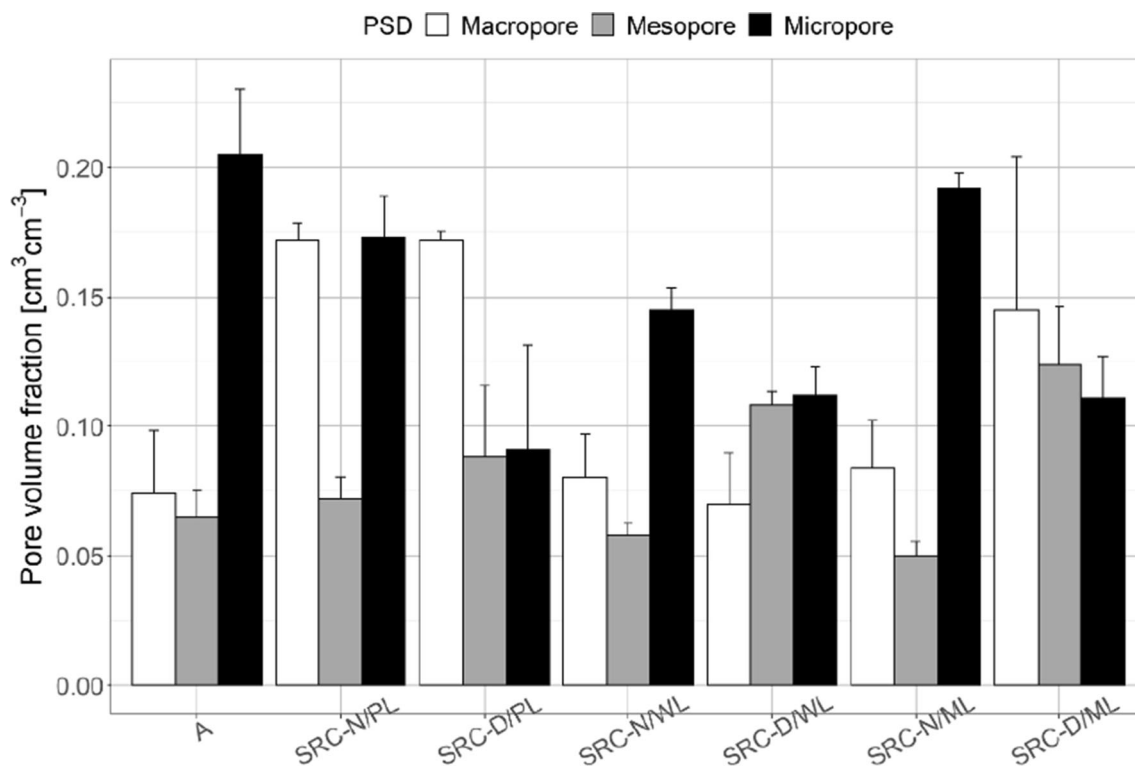


Fig. 5 Pore-size distribution (PSD) from Kosugi-Mualem's parameters considering porosity (Φ) defined as the difference between saturated (θ_s) and the residual (θ_r) water content (Eq. 3) and classified according to Brewer. The PSD is grouped according to the different analysed areas:

(A) agricultural practices, (PL) poplar tree row, (WL) wheeled lane and (ML) middle lane. Standard deviation from topsoil replicates in each field are shown (replicates: AG = 4, SRC-D = 3 in each sub-area and SRC-N = 3 in each sub-area)

further related to a high microbial activity. Our study took place in an early stage SRC field presenting higher total C and N contents compared to an adjacent agricultural site.

Total C and N contents clearly differed when comparing SRC-N to SRC-D and the agricultural field. We attributed these results to the site characteristics such as access to groundwater and the soil texture. The higher content of clay and silt in field SRC-N likely enhanced the nutrient retention, such as the N content. Probably the poor connection to groundwater in field SRC-D limited the total C and N contents in the upper topsoil and consequently the poplar trees yield. Likewise, Zhang et al. [37] reported a decrease in the total soil C and N contents with increasing groundwater distance to surface. The effect of groundwater accessibility was further seen when contrasting poplar tree characteristics on both SRC sites. SRC-N presented larger DBH and height values in contrast to SRC-D (Table 1).

Observed BD values in SRC-N and the agricultural field were found within the same magnitude; however, the tree and the wheeled area particularly were slightly lower. Different from our results, Kahle and Janssen [34] found significantly lower BD in the upper 10 cm of a sandy loam soil under an 18-year-old SRC (1.35 and 1.38 g cm⁻³) compared to medium-high BD in an adjacent agricultural system (1.58 and 1.65 g cm⁻³), probably due to the advanced SRC stage.

Other studies have been conducted in further stages of SRC poplar and willow plantations (18 and 24 years old), where loosened soil was found with substantially lower BD in comparison to agricultural lands [36, 38]. For instance, Kahle et al. [36] also found decreased BD in a 12-year-old poplar SRC with sandy soil in contrast to a set-a-side agricultural land. Similarly, Dong et al. [35] found lower BD in a sandy soil under SRC in contrast to a briefly afforested site which was harvested and abandoned later on. They described that BD under SRC after 3.5 and 5 years were 1.38 and 1.36 g cm⁻³ accordingly, whereas in the abandoned land, the BD was 1.55 g cm⁻³. However, similarly to our findings, Kahle and Janssen [34] found comparable BD between an agricultural field (1.64/1.69 g cm⁻³) and a SRC upon the establishment (1.65 g cm⁻³), though their results correspond to high BD values unlike our results.

Regarding the SRC sub-area assessment, it was expected to find highly compacted soil in the wheel lane within the SRC since the management practices and machinery wheeling induce soil compaction, reducing soil porosity with subsequently increment in BD [39, 40]. For example, Souch et al. [38] reported that in a SRC with sandy clay soil, the machinery compaction significantly increased the BD at 0.1 m depth in the furrowed area from 1.40 to 1.70 g cm⁻³. Surprisingly, in our study, the wheeled area in the SRC-N showed comparable BD to the tree row (Fig. 2).

Our results suggest that the low BD might be a consequence of the potentially increased soil fauna activity under

SRC due to higher total C and N contents, likely loosening the soil and increasing the macropore content. Similar BD values found in the wheeled sub-area in contrast to the agricultural field suggest that the machinery compaction under SRC might not affect the topsoil properties as crop rotation practices. The BD found in the agricultural field was comparable to that described by Kreiselmeier et al. [22] indicating that the influence of soil management (ploughing and seedbed preparation) can still be noticed at the beginning of the growing season for winter wheat.

Overall, BD between SRC fields was higher in field SRC-D even though the same management was applied in both. We attribute such differences in BD values to the poor groundwater access in SRC-D coupled to distinct clay and silt content. As mentioned before, fields exposed to deep groundwater levels may present low C and N contents due to the potential reduced soil fauna activity together with increased BD on the topsoil (0–30 cm) [37]. Within field SRC-D, the highest BD was found in the wheel lane.

Influence of SRC on Infiltration Capacity and Soil Water Content

Field SRC-N presented a higher infiltration capacity in the tree row in contrast to the agricultural field. This may be due to the low BD together with the highest content of macropores in the topsoil. Similar to our results, German and Beven [41] described that soils with high macropore contents are characterized by increased infiltration capacity. Likewise, Gonzalez-Sosa et al. [40] showed higher infiltration capacity in soils beneath tree hedges in contrast to agricultural lands.

Field SRC-D appeared to have similar infiltration capacity in the tree row when compared to SRC-N, indicating that the higher macropore fraction in SRC-D compensated the higher BD. The wheel lane in field SRC-D presented the lowest infiltration capacity within the field and a lower infiltration capacity in contrast to the same lane in field SRC-N, probably related to the high BD, enhancing the machinery effect. The largest infiltration capacity was found in field SRC-N in the middle lane attributed to the lower amount of micropore content (only 29% in comparison to 59% in SRC-N).

Comparing the agricultural field with field SRC-N, water retention capacity values were similar. However, the agricultural field presented slightly higher values. This finding may be related to the higher micropore fraction in this field in contrast to the higher macropore content found in field SRC-N.

Similarly to our results, Kahle and Janssen [34] showed no considerable differences of water content at FC contrasting a SRC with a cropland at 0–10 cm depth. However, they reported that the PAW was higher in the upper soil layer under SRC. Our results differed from their study probably due to the different tree stage. They found higher PAW in an 18-year-old

SRC system, whereas our study took place in the first years of the SRC after the establishment.

The visibly lower water content in field SRC-D at FC and PAW in comparison to SRC-N was attributed to two conditions: different soil texture and site characteristics, namely access to groundwater. Field SRC-D presented around 13% more sand content with accordingly decreased silt-clay particles than SRC-N and enhanced macro-mesopore fraction. These characteristics in combination likely diminished the water retention capacity of the soil in field SRC-D which probably after gravity drainage is not able to hold as much water as the topsoil from field SRC-N.

Influence of SRC on PSD

The SRC field presented an overall higher macropore content with a respective decrease of micropores in contrast to the agricultural field, especially in the tree row. These results may be related to the potential biological activity under SRC due to higher C and N contents, likely enhancing the aggregate stability and widening the pores in the soil [39, 40]. Similarly, Kahle et al. [36] related the increased total pore volume in a 12-year-old poplar SRC to a higher microbial activity.

Despite the identical management practices between both SRC fields, different soil pore distributions were found on the SRC fields. The higher content of macropores in field SRC-D was attributed to the abundant weed roots found in the upper topsoil samples. Root growth as well as decaying roots has been reported as an influencing factor to increase the macropore content in the soil [42].

In the field SRC-N, a distinct enhancement of macropore content was observed. This has an impact in other site characteristics such as the infiltration capacity, BD, or groundwater recharge. Changes were more pronounced in the tree row. A better water infiltration may then further supply deeper soil zones and thus enhance the effective soil water availability of the profile, where the rooting system of the trees can access the water.

Conclusions

Within the SRC plantation, increased macropore fraction with a subsequent decrease of micropores was observed, particularly in the tree row. Enhanced soil BD accounting for a larger water infiltration was seen. Likewise, the topsoil conditions in the wheel lane were rather favourable despite the exposure to machinery compaction. Therefore, we conclude that under favourable conditions, SRC plantations, even in early stages, may have a beneficial impact on the upper topsoil properties in contrast to conventional cropland, likely overcoming the effect of machinery compaction. Such effects were not seen in the field with poor groundwater connection.

Soil properties showed appreciable differences contrasting SRC fields regardless of the identical management practices. They appeared to be susceptible not only to management practices but probably also to the contrasting site characteristics concerning the potential influence of the groundwater table. Thus, our study underlines that great attention must be given to the site selection to establish an SRC, especially to groundwater availability.

Furthermore, this study raises more questions for further investigation related to the SRC impact on soil properties, for instance including a more robust sampling design to cover analysis in deeper horizons to supplement our findings. Likewise, it would be interesting to expand studies related to topsoil properties using the Kosugi's bimodal hydraulic model to assess the impact of SRC with different tree ages (different SRC stages), diverse soil textures and varying access to groundwater.

Moreover, accurate information of soil properties is fundamental for the modeling of water fluxes of SRC systems. Thus, our study provides knowledge regarding the spatially differentiated variability of soil physical and hydraulic properties, which may account for a better quantification of soil water fluxes in hydrological models.

Despite some limitations in the results, our study and the developed methodology provide a framework for future studies to assess the impact of SRC on soil hydraulic properties for a better and sustainable resource management.

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Data Availability The raw data is proprietary but can be disclosed by sending a motivated request to the corresponding author.

Declarations

Conflict of Interest The authors declare no conflicts of interest.

Ethics Approval and Consent to Participate This study did not include human or animal testing. All individuals involved with the experiment were informed about the study purpose and methods and agreed to participate.

Consent for Publication All partners agreed with publication in the present form.

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