Environmental Technology & Innovation 31 (2023) 103143

Contents lists available at ScienceDirect

Environmental Technology & Innovation

journal homepage: www.elsevier.com/locate/eti

Improving crop nutrition, soil carbon storage and soil physical fertility using ramial wood chips

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ARTICLE INFO

Article history:
Received 2 January 2023
Received in revised form 27 March 2023
Accepted 7 April 2023
Available online 13 April 2023

Keywords:
Soil quality
Macro and micronutrients
Wood decomposition
Sustainable farming practices
Thermal analysis
Shrinkage curve

ABSTRACT

Ramial wood chips (RWC) amendment has great potential in sustainable agriculture; however more data is needed to assess its effect on soil fertility and carbon (C) storage. In this study, we investigated the effect of a single application of RWC amendment on a silty clay loam soil. During the 5 year experiment, we measured biomass production, grain yields and crop nutrient uptake. At the end of the experiment, we measured soil micro- and macronutrients, soil organic C (SOC) content and thermal stability, microbial biomass C (C_{mic}), and organic C and total N contents in soil particle size fractions. Soil physical properties, including structural porosity, air and water capacity, were also measured. Neither crop biomass production nor grain yields were affected by RWC. However, RWC was found to affect nutrient uptake, with improved N, P and Mg uptakes for the 2nd and 3rd crops after RWC amendment, and decreased Mn, Fe and Zn uptakes in the second half of the study period. The initially low SOC content increased by 10%, mainly in the mineral-associated organic matter fraction, resulting in a higher SOC stability. The increase in SOC following RWC amendment decreased the bulk density and increased the easily available water capacity due to a larger structural porosity. The increased porosity in the 15–30 µm diameter range was ascribed to a change in SOC quality. In conclusion, RWC amendment improved macronutrient uptake in the short term, but decreased micronutrient uptake in the medium term. RWC increased SOC content and positively affected SOC quality, thus improving soil physical properties including water capacity and aeration.

1. Introduction

The use of ramial wood chips (RWC) in agriculture is receiving growing interest from farmers and researchers. This technique was developed in Québec several decades ago to recycle wood residues as a fertilizer, initially for forestry and later for agricultural purposes (Guay et al., 1982; Lemieux and Lapointe, 1990). Currently, RWC is not commonly applied in agriculture, but the need to adopt more sustainable cropping systems in the context of climate change mitigation has

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https://doi.org/10.1016/j.eti.2023.103143

put RWC in the spotlight as an organic amendment with the potential of improving both soil quality and soil organic carbon (SOC) storage.

Numerous mechanisms can influence soil nutrient availability depending on the RWC decomposition stage and soil properties. Positive effects of RWC on soil quality have been reported in the literature (Barthès et al., 2010; Lemieux et al., 2000), for example by increasing availability of nutrients for plants (Salau et al., 1992; Soumare et al., 2002). Since RWC has a high C-to-N ratio (Guay et al., 1981), the initial phase of RWC decomposition can increase the microbial C availability (Ba et al., 2014; Jourgholami et al., 2021) and, in turn, the microbial N demand to the detriment of crops that may face a N deficiency (Lalande et al., 1998; Tremblay and Beauchamp, 1998). Crop yields can therefore decrease the year after a RWC application, particularly in soils with a coarse texture (Beauchemin et al., 1992; N'Dayegiye and Dubé, 1986), but not systematically (WOOFS Technical Guide 2, 2020). This undesirable effect can be avoided by applying N concomitantly with RWC (Beauchemin et al., 1992). On the other hand, an increase in yield from the second crop after RWC amendment is frequently observed and can persist until the 4th crop (Barthès et al., 2010). This can be explained by microbial turnover that likely favours N remobilization from the second crop after the RWC amendment (Lalande et al., 1998; Soumare et al., 2002). Crop uptake of P and K can also increase concomitantly (Soumare et al., 2002).

Considering the influence of SOC on soil quality, the fate of C from RWC and its influence on the quantity and quality of native SOC (i.e., before RWC amendment) is crucial. SOC usually increased one or two years after RWC amendment, except in soils with coarse textures, where the physical and chemical protection of SOC by mineral surfaces is weaker and a positive priming effect may occur (Barthes et al., 2015; Obiefuna, 1991; Salau et al., 1992; Zaater et al., 2018). Actually, in two soils with coarse textures, opposite results were reported, as RWC seemed to increase the particulate organic matter (POM) and humin-C content in the heavy fraction of organic matter (N'dayegamiye and Angers, 1993; Soumare et al., 2002).

RWC is also known to influence soil physical properties, although very few studies have thoroughly investigated its effects. Previous works reported a decrease of soil bulk density with RWC incorporation, but not systematically when it is applied as mulch (Obiefuna, 1991; Salau et al., 1992; Soumare et al., 2002). In addition, RWC was found to increase the wet aggregate stability in the second year after incorporation (Lalande et al., 1998).

In this study we quantified the effect of RWC on air capacity, storage capacity for plant available water, and the pore volume of different pore size ranges, plasma and structural porosity. Shrinkage analysis was used, i.e., a method allowing standardization of all mentioned properties either at a chosen matric potential or swelling state. For instance, differentiating plasma porosity from structural porosity is useful to study different pore functionalities (Kutílek and Jendele, 2008). The very small pore diameters of plasma porosity (i.e., usually <10 μm), also called textural porosity, are water saturated for a wide range of soil moisture levels and shrinks strongly during drying (Sposito, 1973; Tessier, 1990), whilst the larger structural pores serve as storage for easily available plant water and are a habitat for microorganisms, soil fauna and roots. The volume, air and (easily available) water contents of structural pores should influence microbial communities and their activities, crop nutrition, root growth and RWC decomposition. Generally, rapid air and water transfers occur in the structural porosity whereas plasma porosity is responsible for a natural structural regeneration of the soil through shrink-swell processes. Currently, it is unknown how RWC decomposition affects plasma and structural porosities.

In this study, we also measured the grain yield of 5 consecutive crops and the macro- and micronutrient content in the biomass of these 5 cash and cover crops following RWC amendment. Furthermore, we investigated the effect of the single RWC amendment on biological, physical and chemical properties relevant for soil quality and soil functions 5 years after the RWC amendment. More specifically, we examined the macro- and micro-nutrients, SOC content and organic matter stability, microbial biomass C and both plasma and structural soil porosities. Overall, this study quantified the effect of RWC amendment on: (i) grain yields and crop nutrition, (ii) the content and form of organic C in the soil, and (iii) soil physical properties.

2. Material and methods

2.1. Site description and experimental design

A field trial was established in Switzerland at Agroscope-Changins (46°23′55.72″N, 06°14′24.72″E; altitude 432 m) in 2015 on plots showing a silty clay loam texture (IUSS classification). These plots were conventionally cropped since 1965 (Table A1). The field trial was established on a gentle slope with a clay content varying between 202–303 g kg^{-1} and a pH between 6.1–7.9 at 0–10 cm depth. The clay and SOC contents tended to be higher for the RWC plots at the beginning of the field experiment (i.e. before the RWC amendment, Table 1), although not significantly different. The SOC-to-clay ratio was rather homogeneous within the field experiment (variance coefficient = 9%).

Three plot replicates (20 × 12 m) were amended in August 2015 with 150 m^3 RWC ha^{-1} (Fig. 1).

The RWC was produced by a local farmer. Green waste from various tree species including a slight proportion of coniferous (≈5–10%) was stored outside for 10 days before chipping (maximal stem diameter = 10 cm). Three sub-samples of RWC were collected, oven dried and analysed (Table 2).

The RWC was then immediately amended and incorporated using the rototiller. The following years, reduced tillage was performed several times (Table 3).

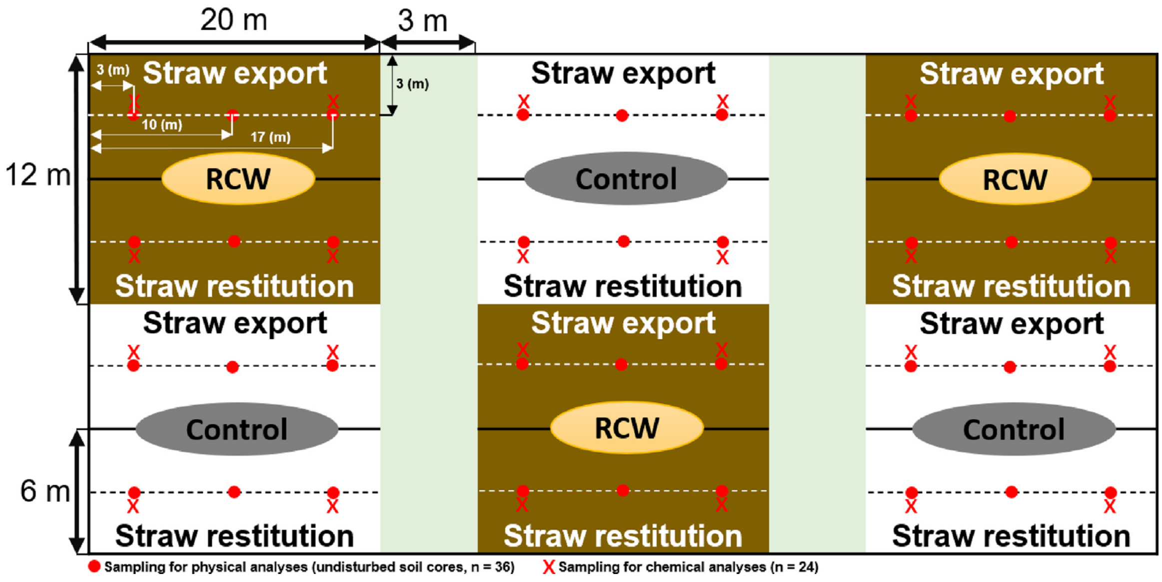

Fig. 1. Scheme of the experimental design.

Table 1
Main soil physical and chemical properties in RWC plots and control plots before RWC amendment (2015).

Treatment	pH	Clay	Sand	SOC	N_{Tot}	P_{min}	P_{Org}	P_{NaHCO3}	K_{AAE}	Mg_{AAE}	Ca_{AAE}	Fe_{DTPA}	Mn_{DTPA}	Cu_{DTPA}	Zn_{DTPA}
		g kg^{-1}				mg kg^{-1}									
Control	6.84	251	104	17.6	2.03	415	283	27.5	188	122	3000	56.7	26.6	2.31	1.83
RWC	6.76	273	94	18.8	2.15	407	284	25.5	176	132	3028	62.9	27.0	2.39	1.39

RWC: Ramial Wood Chip, SOC: soil organic carbon, n: number of observations.

Table 2
Total elemental concentrations of dry RWC.

C	N	P	K	Ca	Mg	C/N	Cu	Fe	Mn	Zn
g kg^{-1}							mg kg^{-1}			
458	8.8	9.3	50	176	13	52	13	1590	93	46

The crop sequence during the experimental period was green manure-winter wheat-green manure-grain maize-winter wheat-rape-winter wheat (Tables 3 and A1). After harvesting in 2016 (Table 3), wheat straw was removed only for half of the plots in order to add a new treatment, "wheat straw restitution and wheat straw removal" which was considered in the field trial as a split plot (20 × 6 m) design (Fig. 1) totalling 12 plots (3 replicates × 4 treatments): RWC amendment and straw export *vs* RWC amendment and straw restitution *vs* control (i.e. no RWC amendment) and straw export *vs* control and straw restitution.

Reduced tillage was performed down to 10 cm depth using a rotary harrow and a rototiller for seedbed preparation and green manure destruction. Plant protection and soil management (Table 3) were carried out for both treatments (control and RWC) according to the Swiss certification scheme Proof of Ecological Performance (Swiss Federal Council 2013). Mineral N fertilization was split-applied on two or three occasions during growing seasons according to the official Swiss fertilization guidelines (Sinaj et al., 2017). Other mineral fertilization (i.e., P, K, Ca, Mg and S) were carried out between 2016 and 2020 (Table 3) according to the official Swiss fertilization guidelines.

2.2. Soil and crop sampling

Undisturbed soil cores for physical analyses were sampled from 3–8 cm depth in July 2020 at 3, 10 and 17 m along the main plot length for a total number of 36 samples (see Fig. A1). In addition, around 500 g of soil was sampled at 0–10 cm depth (i.e., 3 subsamples collected using an auger and mixed) at 3 and 17 m from the plot border along the main plot length in proximity (<50 cm) to the physical sampling location, for a total number of 24 samples.

Wheat straw and biomass of green manure and rapeseed (*Brassica napus*) were collected with a plot combine Haldrup on a 9 m^2 surface area. Yields of winter wheat grains and rapeseed were measured on a 30 m^2 surface, whereas maize yield was measured on the basis of the plants collected along a 20 m long row using an experimental combine.

Table 3
Field trial history.

Date	Crop	Intervention	Amount	Details
5.08.2015	–	RWC spreading	150 m^3/ha	
07.08.2015	Green manure	Sowing	117 kg/ha : Faba bean *Fuego* (20%,), Forage peas *Arkta* (20%), Common vetch *Candy* (20%), Niger *Azofix* (40%)	1/2 dose of *Vicia* (50 kg) and *Pisum sativum* (65 kg) Seeder combined with a rotative harrow
12.10.2015		Destruction		Front shredder
12.10.2015	Winter wheat	Preparation		Rototiller
12.10.2015		Sowing	460 seeds m^{-2}	Great plains
15.03.2016		Fertilization	60 N units	Lonza-MgS-Ammonssalpeter 25
31.03.2016		Fertilization	40 N units	Ammonia Nitrate (27%N, 2.5% Mg)
03.05.2016		Fertilization	40 N units	Ammonia Nitrate (27%N, 2.5% Mg)
06.05.2016		Herbicide		Axial one 1.19 L ha^{-1}, Express Max 0.04 kg ha^{-1} (thistle, bindweed, grasses)
27.05.2016		Fungicide	1.25 L ha^{-1}	Fandango (ear septoriosis)
26.07.2016		Harvest		Combine harvester (Deutz Fahr3370)
05.08.2016	Green manure	Preparation		Rototiller (3–4 cm)
11.08.2016		Sowing	Faba bean *Fuego* (20%, 110 kg ha^{-1}), Forage peas *Arkta* (20%, 40 kg ha^{-1}), Common vetch *Candy* (20%, 37 kg ha^{-1}), Niger *Azofix* (40%, 3.7 kg ha^{-1})	Seeder combined with a rotative harrow (vulpiae destruction)
11.08.2016		Rolling		Improve the germination
23.08.2016		Watering	30 mm	Drought (slow growth of green manure)
27.02.2017		Fertilization		75 P units, 113 K units, 30 Ca units, (Landor 0.20.30)
07.04.2017		Herbicide	7 L ha^{-1}	Roundop Max (weed and thistle regrowth)
15.05.2017		Herbicide	3 L ha^{-1}	(thistle regrowth)
16.05.2017	Grain-Maize	Kerner		All plots
17.05.2017		Preparation		Rotative harrow (alpego)
17.05.2017		Sowing	101000 grains ha^{-1}	Cultivar : ricardinio
18.05.2017		Fertilization	60 N units, 10 Ca units, 6 Mg units	Ammonia Nitrate + Mg
08.06.2017		Herbicide	4 L ha^{-1}	Gardo gold (annual dicotyledons)
08.06.2017		Herbicide	1.3 L ha^{-1}	Elumis (grass)
08.06.2017		Herbicide	0.5 L ha^{-1}	Banvel 4s (perennial dicotyledons)
14.06.2017		Fertilization	60 N units	Urea 46%
21.06.2017		Trichogram		Trichogram
18.10.2017		Harvest		Combine harvester (baural sp2100)
19.10.2017		Destruction		Maize cane shredding
20.10.2017	Winter wheat	Preparation		Rototiller
20.10.2017		Sowing	450 grains m^{-2}	Greats plain
10.11.2017		Herbicide	2.5 L ha^{-1}	Banaril blanco (vulpiae and grass)
13.02.2018		Fertilization	48 N units, 10 Mg units, 16 SO units	
22.03.2018		Fertilization	44 N units, 7 Ca units, 4 Mg units	Ammonia Nitrate + Mg
10.07.2018		Harvest		Combine harvester (deutz fahr 3370)

(*continued on next page*)

2.3. Crop nutrient analysis

Subsamples of fresh biomass were oven-dried (45 °C for 48 h) to estimate the water content before being ground using a Retsch rotor mill (Retsch, GmbH, Haan, West Germany). Total C and total N was measured by flash combustion (Thermo, Flash 2000) (NF ISO 13878). Crop samples were calcinated (550 °C for 5 h) and solubilized in hydrofluoric acid in order to determine total P, K, Ca, Mg, Fe, Mn, Cu and Zn using radial inductively coupled plasma atomic emission spectroscopy (ICP-AES) (Varian Vista RL Simultaneous or Varian 725 ES Simultaneous) (Masson et al., 2010).

2.4. Soil analyses

2.4.1. Chemical analyses

SOC was measured after sulfochromic oxidation (NF ISO 14235). Soil pH was measured using a soil:water ratio of 1:5 (NF ISO 10390). Exchangeable K, Ca and Mg were analysed through ammonium acetate extraction (NFX 31–108)

Table 3 (*continued*).

14.08.2018	Rapeseed	Herbicide	7.5 L ha^{-1}	Roundup max, destruction adventives
17.08.2018		Preparation		Cultivator with kerner
21.08.2018		Sowing	56 grains m^{-2}	Cultivar: trezzor
23.08.2018		Herbicide	4 L ha^{-1}	Brasan trio
27.08.2018		Watering	15 mm	Enhancement of germination and herbicide efficiency
06.09.2018		Watering	37 mm	Drought
20.02.2019		Fertilization	80 N units	Ammonia nitrate 27.5%
21.02.2019		Fertilization	30 Mg units, 60 SO units	Kiserit
22.02.2019		Fertilization	79 P, 118 K, 31 Ca, 6 SO	Landor 0.20.30
28.03.2019		Fertilization	81 N units	Ammonia nitrate 27.5%
29.03.2019		Insecticide	0.2 L ha^{-1}	Talstar (beetles)
25.06.2019		Harvest	Biomass sampling	Haldrup 2010
12.07.2019		Harvest		Heterogeneous yields within plots
14.10.2019	Winter wheat	Preparation		Rotative harrow and rototiller
14.10.2019		Sowing	450 grains m^{-2}	Cultivar : Arina
17.02.2020		Fertilization	47 N units, 8 Ca units, 4 Mg units	ammonia nitrate + Mg,
17.03.2020		Fertilization	50 N units, 8 Ca units, 5 Mg units	ammonia nitrate + Mg,
18.03.2020		Fertilization	80 P units, 120 K units, 32 Ca units, 6 S units	Landor 0.20.30
18.03.2020		Herbicide	1.2 Lt ha^{-1}	Archipel (perennial dicotyledons)
09.08.2020		Harvest		Combine harvester (deutz fahr 3370)

combined with a Thermo Radial ICAP 6000 Series ICP-OES (Thermo Fisher Scientific, Freemont, CA, USA). Total soil N (N_{Tot}) was determined using an elemental analyzer (Thermo Scientific, FLASH 2000, USA) by dry combustion (NF ISO 13878). Total P was analysed through an extraction using 0.25 g of soil in 5 mL of hydrofluoric acid (40%) and 1.5 mL of $HClO_4$ (65%), and a molybdate colorimetric method (Murphy and Riley, 1962) (NFX 31–147). Organic P (P_{Org}) was measured following the procedure of Saunders and Williams (1955). Mineral P (P_{Min}) was calculated by subtracting P_{Org} from total P. Sodium bicarbonate ($NaHCO_3$) extraction was used to determine the soil available P (P_{NaHCO3}) (Olsen, 1954) that was then measured according to Murphy and Riley (1962) (NF ISO 11263). Soil exchangeable Fe, Mn, Cu and Zn were extracted with diethylenetriamine pentaacetic acid (DTPA) and measured by ICP AES (NFX 31–121).

2.4.2. Microbial biomass carbon

Soil microbial biomass C (C_{mic}) was estimated through chloroform fumigation extraction (Vance et al., 1987). Total C of fumigated and non-fumigated samples ($n = 24$) was determined using a TOC/TN auto analyzer (Shimadzu analyzer TOC-V CPH + TNM-1) after (1:10) 0.5 M K_2SO_4 extraction. Values of C_{mic} were estimated according to the coefficient factor Kc = 0.45 (Jenkinson et al., 2004).

2.4.3. Organic carbon and total nitrogen of soil size fractions

Three soil size fractions ($n = 24$), including the coarse POM ($2000 - 200$ μm), the fine POM ($200 - 50$ μm) and the mineral-associated organic matter (MAOM; <50 μm), were separated by sieving after shaking 50 g of soil in 180 mL of water during 16 h with 20 glass beads to break up aggregates (NF X 31 516). Organic C and total N of these fractions were then analysed by sulfochromic oxidation (NF ISO 14235) and using an elemental analyzer (Thermo Scientific, FLASH 2000, USA, NF ISO 13878), respectively.

2.4.4. Shrinkage analysis

Shrinkage analysis was carried out as described by Boivin et al. (2006). Briefly, the undisturbed soil cores ($n = 36$) were equilibrated to a matric potential of -10 hPa using a sand bed, after removal of their PVC sampling cylinder to allow for free swelling. The volume of the samples was measured with the plastic bag method (Boivin et al., 1990) and the undisturbed soil cores were then immediately placed in the shrinkage apparatus. Considering that the drying process is the driver of the shrinkage experiment, the variations in weight and height of soil cores were recorded every 5 min until height and weight remained constant. Micro-tensiometers were inserted into the soil cores to record the matric potential. The air-dried sample volumes were measured again using the plastic bag method. At the end of the measurement, the samples were dried at 105 °C to measure the residual water content. Then, the samples were sieved (2-mm mesh size) to measure the volumes and masses of the coarse fractions to determine the stone content. The particle density was measured with a water pycnometer and ranged from 2.67 to 2.71 g cm^{-3}. The oven-dry weight allowed calculating the gravimetric water content variations using the sample weight variations. Assuming an isometric shrinkage behaviour (Boivin, 2007), volume variations were calculated using the measured variations in height according to Eq. (1):

$$\frac{V}{V_f} = \left(\frac{h}{h_f}\right)^3 \tag{1}$$

with V as the sample volume corresponding to h, the height of the sample at any water content (that decreases during the drying process), V_f and h_f as the final volume and the final height of the sample in air-dry state, respectively.

The XP model was used to analyse the shrinkage curve data in order to quantify the specific volumes of the structural and plasma porosities and the corresponding air and water contents (Braudeau et al., 1999). Briefly, this modelling procedure is fitting transition points between the linear and curvilinear domains of the S-shape shrinkage curve to the measured data of the shrinkage experiment. We used the procedures described by Boivin et al. (2006) for the fitting. The transition points of the shrinkage curve correspond to the plasma shrinkage limit (SL), the plasma air entry (AE), the structural porosity dry point (ML) and the plasma maximum swelling (MS). This allowed to determine the structural ($\mathrm{PORs_{tr}}$) and plasma ($\mathrm{POR_{pl}}$) porosities and their air and water contents on the full water content range. The easily plant available water (EAW) was calculated using the water contents at MS and ML as follows Eq. (2):

$$\mathrm{EAW} = \mathrm{W_{MS}} - \mathrm{W_{ML}} \tag{2}$$

The soil bulk density (D) and pore volumes (POR) at the SL, AE, ML, and MS transitions points of the shrinkage curve are indicated using their abbreviation in subscript (e.g., D_{MS}, $\mathrm{POR_{StrSL}}$). Among the numerous physical properties determined using shrinkage curve analysis, we focused mainly on those affected by the RWC amendment.

2.4.5. CoreVESS evaluations

Soil structure quality was visually evaluated with the CoreVESS method (Johannes et al., 2017b) on the same samples that were used for shrinkage analysis. In summary, after shrinkage analysis, the samples were equilibrated at −100 hPa (field capacity) in a sandbox, prior to visual examination. Scores from 1 to 5 were given to each sample by observing the following criteria for soil structure quality: breaking difficulty, aggregate shape, and visible porosity. According to the authors of VESS (Ball et al., 2017), a score of one denotes a very good structure, a score of 5 a very poor structure and a score of 3 is the limit between good and poor structure quality. The visual evaluations were performed as blind test independently by two people in order to have visual reduce bias.

2.4.6. Soil texture and thermal analysis

An aliquot of the 2 mm-sieved undisturbed soil core ($n = 36$) was used to determine soil texture through the pipette method (five fractions, NFX 31 107) and SOC through sulfochromic oxidation (NF ISO 14235), while another aliquot was used to carry out the thermal analysis using a thermogravimetric analyser coupled with simultaneous differential scanning calorimetry (TGA-DSC 3+, Mettler Toledo, Switzerland). About 20 mg of each sample were placed in an alumina crucible and heated from 30 to 700 °C at 10 °C $\mathrm{min^{-1}}$ under an oxidizing atmosphere of air at a flow rate of 100 mL $\mathrm{min^{-1}}$. The energy density (J g $\mathrm{sample^{-1}}$) was calculated by integrating the DSC heat flux (in mW) over the exothermic region 105 to 550 °C and normalizing by the mass loss (and the SOC) (Giannetta et al., 2022; Peltre et al., 2013). The temperatures at which half of the energy was released (DSC-T_{50}) and half of mass was lost (TGA-T_{50}) were also calculated.

2.5. Data analysis

Statistical analyses were carried out using R 3.01 software (R Core Team, 2013). If required by the model, normality assumption was checked with the Shapiro test function (stats package).

First, the effects of the RWC amendment and the straw export were tested on all measured variables using the lm function. In addition, as the sampling strategy resulted in a hierarchical data structure (i.e., each plot was sampled three times, namely at 3, 10 and 17 m from the plot border), plot effect was tested on all measured variables using the lm function. Neither plot effect (testing if variability across plots was higher than within plots), nor straw restitution effect ($p < 0.05$) was detected on any measured variable, i.e., in soil variables (biological, physical, and chemical properties) and crop variables (grain yields, biomass production and biomass nutrients). Consequently, we tested the RWC effect using the entire dataset, i.e., regardless of straw restitution.

Means of measured variables since the beginning of the trial for plots with and without RWC amendment were all compared using t-tests.

In mineral soils, SOC is known to be generally associated to fine particles, i.e., the higher the clay contents the more SOC is stabilized (Dexter et al., 2008). Therefore, the initial difference in clay content between the RWC plots and the control plots at the beginning of the field trial (i.e. before RWC the amendment) (Table 1) needed to be corrected statistically. The initially higher clay content in RWC plots would have confounded the difference in SOC due to the effect of RWC amendment. Therefore, variation partitioning (Peres-Neto et al., 2006) of SOC was carried out to test and quantify (i) the influence of the clay gradient on SOC content independently of the RWC effect, (ii) the RWC effect on SOC content also explained by (i.e. controlled or collinear with) the clay gradient, and (iii) the RWC effect on SOC content independently of the higher clay content effect on RWC plots compared to control plots. For that purpose, we used Helmert contrasts (Legendre and Legendre, 2012) to code for the RWC treatment combined with varpart, rda, RsquareAdj and Anova functions (*vegan* package).

Additionally, it is known that many soil properties are driven by SOC content (Kay, 2018; Plaza et al., 2018). Therefore, in order to quantify to what extent the influence on properties is due to either the increase in SOC by RWC amendment or to the independent effect of RWC itself, a variation partitioning was carried out. Variation partitioning was done as

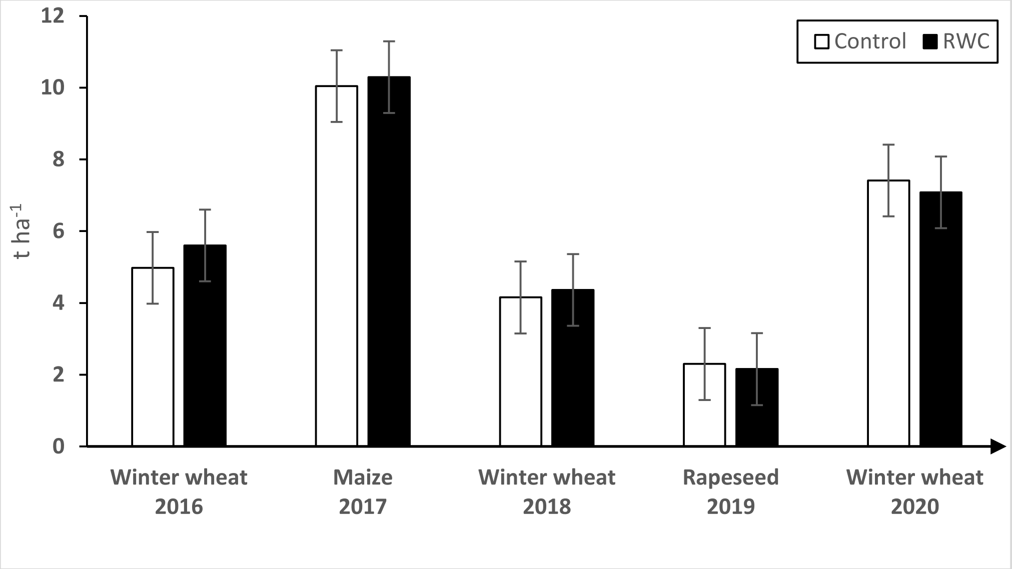

Fig. 2. Grain yields during the studied crop rotation period for plots without (control) and with ramial wood chips (RWC).

previously detailed for each soil property influenced by RWC effect ($p < 0.05$) to test and quantify separately (i) the variance of soil properties explained concomitantly by both, the RWC effect and the variance in SOC content and (ii) the RWC effect that was independent from (i.e. not controlled by) the variance of SOC content.

When the RWC effect on a soil variable was concomitantly explained (i.e., fully controlled) by SOC, we considered that the RWC effect influenced the variable proportionally to the indirect effect of RWC on SOC content. Thus, we quantified the "net" effects of RWC on soil properties that were governed (or controlled) by SOC regardless of the influence of the variations in SOC at the beginning of the trial (i.e., before RWC amendment) between plots with and without RWC. Based on the observed effect on a soil property, we applied the following correction to calculate the net effect of a treatment on this soil property Eq. (3):

$$\text{Net effect} = \text{Observed effect} \times \left(1 - \frac{\text{mean}(\text{SOC}_{2015_{\text{RWC}}}) - \text{mean}(\text{SOC}_{2015_{\text{Control}}})}{mean(\text{SOC}_{2020_{\text{RWC}}}) - \text{mean}(\text{SOC}_{2020_{\text{Control}}})}\right) \tag{3}$$

where the "net effect" (in %) is only due to the RWC amendment, whereas the "observed effect" (in %) is the effect between RWC and control plots measured in the field trial; $\text{SOC}_{2015\text{RWC}}$ is the SOC content in the RWC plots in 2015, $\text{SOC}_{2015\text{Control}}$ is the SOC content in the control plots in 2015, $\text{SOC}_{2020\text{RWC}}$ is the SOC content in the RWC plots in 2020, $\text{SOC}_{2020\text{Control}}$ is the SOC content in the control plots in 2020. We calculated the net effect even for variables whose RWC effect was partly controlled by SOC. In such cases, we included "<" to indicate that "net effect" is likely underestimated.

3. Results

3.1. Grain yields and biomass nutrients

The grain yields of wheat, maize and rapeseed for 2016 to 2020 were not affected by RWC (Fig. 2). For nutrients in the plant biomass (Table 4), we observed that, since 2016, N concentration tended to be higher in the RWC treatment and was significantly higher ($p < 0.05$) in the green manure biomass of 2016 compared to control. P and Mg concentrations were significantly higher only in the wheat straw and green manure biomass of 2016. Regarding the micronutrients, there was a general trend for lower concentrations in the RWC treatments during the second half of the study period (Table 4).

3.2. Soil nutrients and organic carbon

Soil N_{Tot} was marginally higher in 2015 before the beginning of the field trial in the RWC plots although no statistically significant difference to the control plots ($p < 0.05$) was detected (Table 1). In 2020, N_{Tot} and P_{Org} were significantly higher ($p < 0.05$) for the RWC treatment with, respectively, 2.11 and 307 mg kg^{-1} for the control treatment and 2.38 and 331 mg kg^{-1} for the RWC treatment (Table 5). It is noteworthy that the increase of degrees of freedom (i.e., the number of collected samples) from 2015 to 2020 enhanced the sensitivity to detect a RWC effect in 2020.

At the beginning of the trial in 2015, the SOC content was 17.6 g kg^{-1} in the control and 18.8 g kg^{-1} in the RWC treatment (Table 1). As mentioned above, this slight (not statistically significant) difference is due to a clay gradient in the

Table 4
Crop biomass production and nutrients concentration in straw of winter wheat and plant biomass of green manure and rapeseed.

Year	†Crop	n	RWC	Yield	N	P	K	Ca	Mg	Cu	Fe	Mn	Zn
				$t\ ha^{-1}$	$g\ kg^{-1}$					$mg\ kg^{-1}$			
2016	Winter wheat	6	No	NA	5.9	0.43 b	8.5	2.20	0.41 b	2.1	56.1	23.8	5.5
			Yes	NA	6.3	0.72 a	8.5	2.5	0.50 a	2.0	42.8	19.1	6.6
	Green manure	12	No	3.1	3.30 b	0.48 b	4.28	1.86	0.26	10.2	239.7	58.7	39.9
			Yes	3.1	3.61 a	0.53 a	4.19	1.63	0.26	10.1	204.7	50.7	41.3
2019	Rapeseed	12	No	8.4	1.57	0.34	2.04	2.16	0.2	4.0	124.1 a	34.3 a	24.3 a
			Yes	8.1	1.65	0.34	2.02	2.11	0.2	4.0	85.6 b	27.1 b	21.6 b
2020	Winter wheat	12	No	9.4	0.71	0.07	1.37	0.33	0.07	2.5	32.8	15.8	11.74
			Yes	8.8	0.70	0.08	1.38	0.33	0.07	2.2	28.1	10.7	11.51
	Green manure	12	No	4.0	2.63	0.54	4.88	3.10	0.22	8.8	242.4	56.5	27.20 a
			Yes	5.2	2.71	0.56	5.01	3.14	0.21	8.9	180.1	47.6	24.34 b

†There is no data for the first green manure crop established during the 3 months following the RWC amendment and for maize and wheat in 2017 and 2018, respectively.
Different letters indicate significant differences ($p < 0.05$) between control and RWC amendment.

Table 5
Soil physical and chemical properties in RWC plots and control plots five years after RWC amendment (2020).

Treatment	pH	Clay	Sand	SOC	N_{Tot}	C_{mic}	N-NH_4	N-NO_3	P_{min}	P_{Org}	P_{NaHCO3}	K_{AAE}	Mg_{AAE}	Ca_{AAE}	Fe_{DTPA}	Mn_{DTPA}	Cu_{DTPA}	Zn_{DTPA}
		$g\ kg^{-1}$				$mg\ kg^{-1}$												
Control	6.88	241	124	17.6 b†	2.11 b	180	1.00	11.9	446	307 b	31.0	276	145	3037	57.7	13.3	1.83	1.29
RWC	6.93	269	107	20.7 a	2.38 a	164	0.90	11.4	450	331 a	33.6	292	163	3049	55.6	13.2	1.87	1.19

†Different letters indicate significant differences ($p < 0.05$) between fertilization treatments (Control vs RWC). RWC: Ramial Wood Chip, SOC: soil organic carbon, n: number of observations.

experimental field. Given the importance SOC has for most soil physical and chemical properties, this "clay-induced SOC difference" needs to be considered, as explained in the methods section. Indeed, the clay gradient explains 53% ($p < 0.001$) of the SOC variance (Table 6). Variation partitioning showed that among the 21% of the SOC variance controlled by the RWC effect, only 7% was uncontrolled by the clay gradient, whereas the remaining (14% of SOC variance) was concomitantly explained by the clay content. The relative difference in SOC between RWC and control plots increased from 2015 to 2020 by 60% Eq. (1). Once the influence of clay content has been taken into account and was removed, the net effect of the RWC treatment on SOC was +10.3% (Table 6).

Overall, RWC amendment increased the SOC content. In 2020, SOC content was 17.6 g kg^{-1} in the control treatment and 20.7 g kg^{-1} in the RWC treatment ($p < 0.05$). Therefore, the SOC-to-clay ratio in the RWC treatment increased from 0.069 in 2015 to 0.077 in 2020, whilst it remained nearly unchanged the control remained (from 0.070 to 0.073). The 150 m^3 ha^{-1} of RWC applied in the RWC treatment represent an input of around 34.4 t C ha^{-1}, considering its C concentration (i.e. 45.8%, Table 2) and assuming a RWC density of 0.5 t m^{-3} (which is an estimate in a range of values previously reported) (Chave et al., 2006; Hacke et al., 2001). Assuming a homogeneous (air-dried) bulk density in the 0–10 cm soil layer, the net increase in SOC with RWC (+1.87 g kg^{-1}) represents a C stock of 2.7 t ha^{-1} corresponding to 7.8% of the C input through the RWC amendment.

The C_{mic}-to-SOC ratio decreased with RWC (Table 6), indicating a lower microbial biomass C availability of the SOC. The C_{mic}-to-SOC ratio was neither related to clay nor to SOC.

Thermal analyses showed that RWC increased the energy released per unit of SOC due to the increase in more biochemically recalcitrant organic matter (Table 6). RWC explained 37% of the variance of the energy released per unit of SOC. Among these 37%, 22% were not controlled by the variance in SOC content, indicating that RWC amendment modified also the SOC quality, increasing its thermal stability.

The RWC amendment tended to increase C content in the coarse and medium soil size fraction (not significantly) whereas C increased significantly ($p < 0.05$) in the fine soil size fraction (<0.05 mm, Fig. 3). The variance of SOC explained the C and N contents in the soil fractions, especially in the finest one, i.e., $C_{Frac<0.05\ (mm)}$ and $N_{Frac<0.05\ (mm)}$ (Table 6), while the clay effect was not significant. Therefore, the RWC effect was significant only for $C_{Frac<0.05\ (mm)}$ and $N_{Frac<0.05\ (mm)}$ and was due to the SOC increase by the RWC treatment (indirect effect).

3.3. Soil structure quality and physical properties

As expected, SOC and clay were related with most of the physical properties determined in this study (Table 6). Despite the initial variations in SOC and clay in the field trial, an improvement of soil physical quality by the RWC treatment can be observed calculating a net effect of the treatments, which was highlighted through the variance partitioning statistical method and are summarized in Table 6. Incorporating RWC in the soil decreased bulk density from 1.48 to 1.42 g cm^{-3}

Table 6
Means of SOC and soil physical properties as significantly affected by the ramial wood chips (RWC) treatment ($p < 0.05$). The observed effect in 2020 and the net effect (Eq. (1)) are reported in the columns entitled "Observed" and "Net", respectively. The percentages of the variance in physical soil properties ($n = 36$) explained by clay and SOC (i.e., adjusted R^2 of the linear relationships) are indicated in the columns entitled "Clay" and "SOC". Slope coefficients (+ or −) are in parentheses. For each soil property, the lowest adjusted R^2 between clay and SOC is indicated (in italic grey) and the highest adjusted R^2 identified the variable used for variation partitioning (i.e., generally SOC). Variation partitioning results of the physical soil properties are presented in the column entitled "RWC Var. Part.". This value indicates the adjusted R^2 of total RWC effect, while the value in brackets is the adjusted R^2 of RWC effect excluding the effect of SOC increase. The lack of parentheses indicates that RWC effect is fully controlled by (or totally due to) SOC (or clay).

Soil properties	**Means**		**RWC effect**		**Clay**	**SOC**	**RWC Var. Part.**
	Control	**RWC**	**Observed**	**Net**			
			-------------%-------------		-----------% variation explained-----------		
SOC, g kg^{-1}	17.6	20.7	*+ 17.1*	+ 10.3	53^{***}	-	21^{**} (7^{*})
En. Dens., J mg SOC^{-1}	9.93	11.45	*+ 15.4*	> + 9.3	*(+) 4*	(+) 16^{**}	37^{***} (22^{***})
†C_{mic}-to-SOC	9.07 10^{-3}	7.35 10^{-3}	*- 19.1*	- 19.1	NS	(-) 20	42^{***} (19^{**})
†$C_{Frac < 0.05\ (mm)}$, g kg^{-1}	21.2	23.8	*+ 12.5*	+ 7.5	NS	(+) 83^{***}	21^{*}
†$N_{Frac < 0.05\ (mm)}$, g kg^{-1}	2.62	2.87	*+ 10.0*	+ 6.0	NS	(+) 84^{***}	15^{*}
D_{dry}, g cm^{-3}	1.48	1.42	*- 2.1*	- 1.3	*NS*	(-) 9^{*}	12^{*}
D_{MS}, g cm^{-3}	1.38	1.29	*- 6.7*	- 4.0	*(-) 27^{***}*	(-) 58^{***}	26^{**}
$POR_{Str\ SL}$, cm^3 g^{-1}	0.119	0.177	*+ 49.4*	+ 29.8	*NS*	(+) 19^{**}	18^{**}
$POR_{Str\ MS}$, cm^3 g^{-1}	0.074	0.122	*+ 64.6*	+ 39.0	*(+) 9^{*}*	(+) 22^{**}	16^{**}
$A_{-100\ hPa}$, cm^3 g^{-1}	0.076	0.110	*+ 45.0*	+ 27.2	*NS*	(+) 18^{**}	14^{**}
$POR_{Tot-100\ hPa}$ cm^3 g^{-1}	0.353	0.397	*+ 12.5*	+ 7.5	*(+) 17^{**}*	(+) 50^{***}	21^{***}
EAW, g g^{-1}	0.022	0.050	*+ 121.9*	+ 73.6	*(+) 15^{*}*	(+) 28^{**}	14^{*}
$POR_{37.5-60\ \mu m}$, cm^3 g^{-1}	0.010	0.015	*+ 77.6*	+ 46.8	*(+) 10^{*}*	(+) 13^{*}	21^{**}
$POR_{30-37.5\ \mu m}$, cm^3 g^{-1}	0.005	0.007	*+ 33.9*	+ 20.5	*(+) 13^{*}*	(+) 20^{**}	20^{**}
$POR_{15-30\ \mu m}$, cm^3 g^{-1}	0.017	0.023	*+ 28.9*	> + 17.4	*(+) 9^{*}*	(+) 27^{**}	33^{***} (12^{**})

Linear models are significant at $^{*}p \leq 0.05$, $^{**}p \leq 0.01$ and $^{***}p \leq 0.001$.
SOC, soil organic carbon content ; En. Dens., is the energy released per unit of SOC; D is the bulk density; POR_{Str}, is the structural porosity. The subscripts SL and MS correspond to shrinkage curve transition point: shrinkage limit and maximum swelling; $A_{-100\ hPa}$ and $POR_{Tot-100\ hPa}$ are the gravimetric air content and total porosity at −100 hPa matric potential; EAW is the easily plant available water; POR is the porosity with pore range indicated as subscript.
†Measured with samples collected for chemical analyses ($n = 24$) whereas clay content was analysed only on samples collected for physical analyses ($n = 36$).

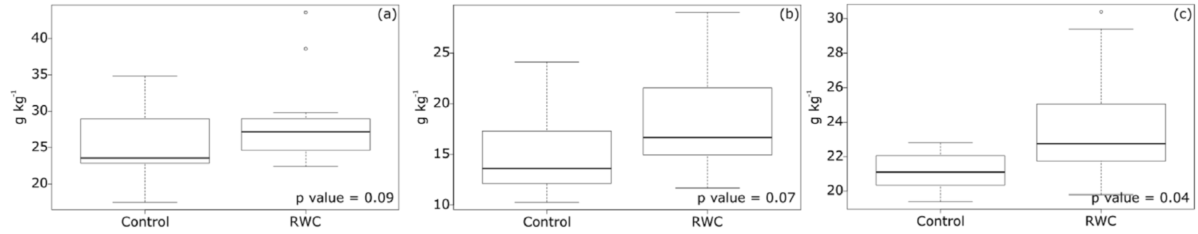

Fig. 3. Carbon content ($n = 24$) in three soil size fractions namely the coarse POM: 2 − 0.2 mm (a), the fine POM: 0.2 − 0.05 mm (b) and the MAOM: <0.05 mm (c), p value of treatment effect (i.e. RWC vs control) is indicated.

at dry state ($p < 0.05$) and from 1.38 to 1.29 g cm^{-3} at MS ($p < 0.01$), and therefore a decrease of 2.1 and 6.7% could be measured, respectively. This means a decrease of 1.3 and 4%, respectively, attributable as net effect to the RWC treatment. Similarly, total porosity at −100 hPa increased by 7.5% as net effect of the RWC treatment; this is mainly caused by an increase in structural porosity with up to 39% increase for the structural porosity at MS. On the other hand, plasma porosity was not affected by RWC and remained around 0.281 and 0.282 cm^3 g^{-1} on average. The increase in structural porosity ($p < 0.01$) (i.e. higher increase at MS point than at ML point), resulted in a relative net increase of 73.6% in easily available water capacity ($p < 0.05$). Air capacity was improved as shown by gravimetric air content at −100 hPa, which increased from 0.075 to 0.110 $cm^3\ g^{-1}$ between control treatment and RWC ($p < 0.01$, Table 6). Among this 45% increase, 27.2% of it can be attributed to the amendment of RWC. As previously stated, most of the improvements in soil physical properties are linearly related to the increase in SOC caused by the organic matter input of the RWC amendment. However, a part of the increase in the volume of pores size 15 to 30 μm diameter is not fully explained by the increase in SOC (as indirect effect of the RWC treatment). This indicates an effect of RWC treatment which is additional to those due to the SOC increase. The RWC treatment had an average CoreVESS score of 2.17, while the control treatment had an average CoreVESS score of 2.44. Although this difference was not statistically significant, it shows a tendency for structural improvements after a RWC amendment.

4. Discussion

4.1. Grain yields and biomass nutrients

In our silty clay loam soil, the RWC amendment did not influence the grain yields or the plant biomass production of the entire crop rotation (Fig. 2 and Table 4), in contrast to what has been observed for soils with coarser textures (Beauchemin et al., 1990; N'Dayegiye and Dubé, 1986; Soumare et al., 2002; Tremblay and Beauchamp, 1998). In coarse-textured soils with low soil N content, grain yields of the first crop established after the RWC amendment decreased, followed by an increase for subsequent crops, according to fluctuations in N availability (Barthès et al., 2010). In this study, a green manure crop was established immediately after the RWC amendment to avoid a possible decrease of the cash crop yield due to N limitation (Beauchemin et al., 1992; N'dayegamiye and Angers, 1993; N'Dayegiye and Dubé, 1986). In the following crops, N concentration in plant biomass was higher in the areas amended with RWC, particularly for the green manure in 2016, likely due to a peak in mineral soil N (Barthès et al., 2010). The N mineralization of the RWC was probably slow due to the high C-to-N ratio (C-to-N = 52, Table 2), especially when compared to organic fertilizers such as cattle manure (C-to-N = 35) or poultry manure (C-to-N = 12) that can have a large part of their N mineralized after few weeks (Aulakh et al., 2000; Qian and Schoenau, 2002). At the end of the rotation in 2020, no significant effect of the RWC amendment on N concentration in plant biomass or on NO_3^- or NH_4^+ was detected (Tables 4 and 5). The significant increase of N_{Tot} (Table 5) and N associated with the finer soil mineral fractions, i.e. $N_{Frac<0.05\ (mm)}$ (Table 6), suggests that N provided by RWC was stabilized in the MAOM fraction in a more stable form (Aoyama et al., 1999; Samson et al., 2020).

The effects of RWC amendment on soil P availability are not straightforward, as it has previously been found to be positive, negative or negligible (Barthes et al., 2015; Kwabiah et al., 2003; Soumare et al., 2002; Tremblay and Beauchamp, 1998). In our study, RWC increased the P concentration in wheat straw and in green manure grown in 2016 (Table 4). The reported increase in soil labile C following RWC amendments (Fujisaki et al., 2015) would be expected to promote P availability due to both competition for P fixing sites with organic molecules and to the propensity of organic molecules to chelate P (Guppy et al., 2005; Von Wandruszka, 2006; Yang et al., 2019). This would be consistent with the increase in SOC, soil available P and P in cherry leaves observed in the vicinity of pile of forest harvest residues (McCavour et al., 2014). However, this was a short-term effect since no RWC effect was observed on P concentrations of the later crops 2019 and 2020 or on soil available P (P-$NaHCO_3$) in 2020. The P_{Org} accrual (Table 5) may be due to microbial and chemical processes respectively, e.g. microbial transformation of P-$NaHCO_3$ into P_{Org} (Chen et al., 2019), or P binding with organic molecules (Huang et al., 2017). Alternatively, P_{Org} could be inherited from P contained in RWC following its decomposition. These hypotheses should be tested in future studies.

The increase in Mg availability after a RWC amendment during the winter wheat cultivation in 2016 was probably due to a Mg flush which can be observed during wood decomposition (Lasota et al., 2018).

The amendment of RWC decreased Mn, Fe and Zn concentrations in different crops (Table 4). It is possible that there was competition between crops and soil microorganisms that may have immobilized the micronutrients required to decompose RWC. Microorganisms can adapt their strategies to oxidize soil organic molecules according to Mn and Fe availability (Jones et al., 2020). Manganese is a prevalent driver of forest litter decomposition since lignin oxidation occurs due to fungal enzymes made up of Mn^{3+} as the electron acceptor (Keiluweit et al., 2015). Manganese (Mn^{3+}/ Mn^{4+}) is then accumulated as oxide precipitates in the dead fungal residues which lowers the level of Mn available for crops. Also, Zn is a component of fungal enzymes and structural proteins and as such influences the fungal communities from deadwood (Purahong et al., 2016). In summary, these results highlight an increase of macronutrient availability, especially during the first and the second years after RWC amendment, and a decrease of the availability of micronutrients five years after the amendment.

4.2. Soil organic carbon content and stability

By taking into account the initial variability of SOC due to clay content variability at the experimental site (Fontana et al., 2015; Schäffer et al., 2008), we observed a positive net effect of the RWC on SOC compared to the controls ("indirect RWC effect", Table 6). RWC incorporation using rotary harrow likely favoured SOC accumulation in our experiment since this practice is reported to promote SOC accumulation more than mulching (Félix et al., 2018). Despite the fact that the 150 $m^3\ ha^{-1}$ RWC amendment is in the upper range of amounts used in most studies (Barthes et al., 2015), recommendations are between 150 and 300 $m^3\ ha^{-1}$ (Caron and Lemieux, 1999; Gilli, 2012; Lemieux et al., 2000).

However, amounts of available RWC can be limiting, especially for field crop areas. In addition, the purchase of RWC for field crops can be prohibitively expensive and should ideally be produced on-farm. On the other hand, RWC amendment can sustainably improve the soil quality. In our study, we could still observe an increase in the SOC content 5 years after RWC amendment. The SOC content of the upper layer increased from 18.8 to 20.7 g kg^{-1} (Table 5) corresponding to a C retention coefficient of around 7.8%, which is in the magnitude usually observed for organic manure (Maillard and Angers, 2014). In fact, a SOC increase in the top 20 cm was frequently observed after a RWC amendment (N'Dayegiye and Dubé, 1986; Lalande et al., 1998; Tremblay and Beauchamp, 1998; Ba et al., 2014; Montaigne et al., 2018), but this pattern was not always consistent (Barthes et al., 2015; Félix et al., 2018). In contrast, the wheat straw restitution, totalling ∼10 t C ha^{-1}, did not influence SOC in our experiment, likely because the amount of C in the wheat straw was much lower than the ∼35 t C ha^{-1} in the RWC amendment and SOC from straw generally accumulates poorly in the soil due to a high biological turnover (Curry and Byrne, 1982; Maltas et al., 2018).

The RWC effects on SOC energy density and C_{mic}-to-SOC highlighted an influence on SOC quality (Table 6). This is also confirmed by statistical models (Table 6), as around half of the RWC effect on these two variables was not explained by the variation in SOC content, suggesting an important effect of a change in SOC quality. Surprisingly, the RWC effect did not influence the most thermoresistant molecules (i.e. 400–550 °C, not shown), suggesting that lignin contained in the RWC was largely decomposed (Giannetta et al., 2018; Peltre et al., 2013). Likely, an increase of soluble C in the first months after RWC amendment favoured the lignin decomposition (Fujisaki et al., 2015; Klotzbücher et al., 2011; Tremblay and Beauchamp, 1998). Other factors may also have promoted the lignin decomposition with RWC amendment, for instance the increase in N availability (Table 4) or of soil porosity that affected soil water content (Table 6) (Donnelly et al., 1990; Melillo et al., 1982). The lack of a RWC effect on $C_{\mathrm{Frac2-0.2\ (mm)}}$ and $C_{\mathrm{Frac0.2-0.05\ (mm)}}$ (Fig. 3) suggests that in our study POM was poorly increased by undecomposed RWC, as was observed after a shorter lag (2 years) in a coarser textured soil (Soumare et al., 2002). Rather, $C_{\mathrm{Frac<0.05\ (mm)}}$ and $N_{\mathrm{Frac<0.05\ (mm)}}$ were the most affected by RWC (Table 6). This finding is in agreement with N'dayegamiye and Angers (1993) who also reported an increase in the MAOM fraction after nine years with biennial addition. In our study, the increase of MAOM along with the lower C_{mic}-to-SOC ratio after RWC amendment (Table 6) suggests a reduced C availability for microorganisms and an improved C physical and chemical protection, respectively. The low SOC-to-clay ratio (ranging from 0.058 to 0.105 for all studied plots, with a mean ratio of 0.076 for plots with RWC treatment in the 3–8 cm depth) likely favoured the formation of MAOM, considering that clay can be saturated with complexed C at a SOC-to-clay ratio of around 0.10 (Dexter et al., 2008). Values of SOC-to-clay ratio of this study are far below the 0.10 threshold proposed by Johannes et al. (2017a) as a realistic goal for SOC management and even below the 0.08 threshold, indicating that SOC management needs to be adapted urgently at our experimental site. Altogether, our results show that a RWC amendment increased the amount of SOC in a more stabilized form.

4.3. Soil physical properties

In accordance with other studies (Obiefuna, 1991; Saini and Hughes, 1975; Soumare et al., 2002), our data show that many physical properties improved after a single RWC amendment. The modest difference in SOC between RWC and control treatments (Table 6), combined with a reduced tillage regime that could have negatively affected soil structure quality, decreased the chances of visually observing a difference between control and RWC treatment. This, in addition to the low sensitivity of the method, can explain why the results of CoreVESS visual evaluations showed a tendency towards improvement after RWC amendment, but were not statistically significant. On the other hand, the sensitivity of the shrinkage analysis allowed us to detect a positive influence of the RWC amendment on the measured soil physical properties. Overall, RWC increased structural porosity and therefore increased the easily available water capacity for crops, while bulk density decreased (Table 6).

Positive relationships between SOC and soil physical properties are well known (Kay, 2018; Saini, 1966). In our study, the SOC increase due to the RWC amendment (“indirect effect”) explains partly the positive RWC effects observed on the physical properties of the soil (Table 6). However, given that the soils of our experimental field can be considered as C depleted, it is not surprising that soil physical properties were also rather poor. For instance, the coarse porosity can be considered low, especially in the control treatment. With values of gravimetric air content at −100 hPa ranging from 0.036 to 0.145 cm^3 g^{-1} for the control treatment, half of these samples were below the reference value of 0.068 cm^3 g^{-1} proposed by Johannes et al. (2019) as an indicator for soil structure quality, thus indicating that soil management must be improved. With values ranging from 0.059 to 0.244 cm^3 g^{-1}, the RWC treatment (data not shown) seems to have improved the situation, as almost all samples in the RWC treatment had an acceptable soil structure quality, i.e., they were above the reference value.

Although the improvement in soil physical quality was mostly directly related to the increased SOC (“indirect effect of RWC”), it is noteworthy that the incorporation of RWC in the soil had an additional effect on soil physical properties. Indeed, the increase of the volume of pore with 15 to 30 μm equivalent diameter was additionally explained by a direct effect of the RWC treatment. This suggests that the modified SOC quality in the RWC treatment directly improved water retention in this pore class. This interpretation is supported by the relationship between $P_{30-15\ \mu\mathrm{m}}$ and the SOC energy density (adj $R^2 = 0.10$, $p < 0.05$) or C_{mic}-to-SOC ratio (adj $R^2 = 0.16$, $p < 0.05$). Overall, the RWC amendment resulted in a positive influence of stabilized C on soil porosity, including water retention capacity and aeration.

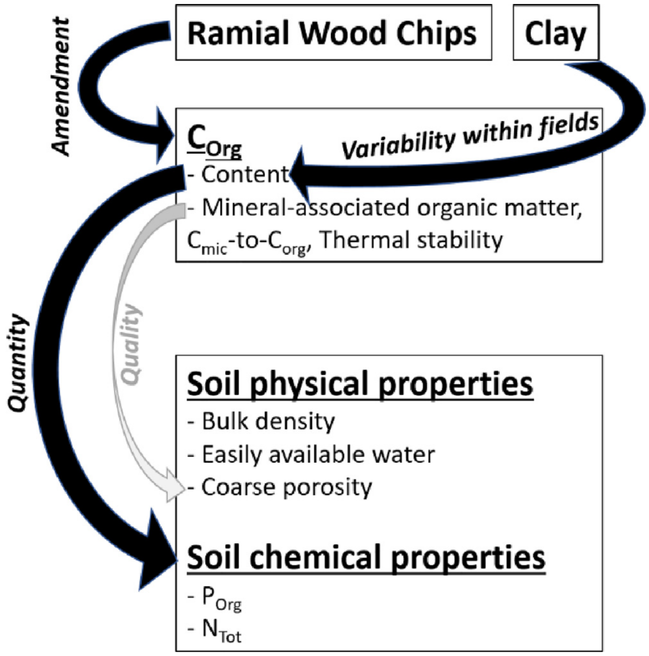

Fig. 4. Ramial wood chips (RWC) amendments influence soil physical and chemical properties through an increase in SOC content which is originally driven (i.e., before RWC amendment) by clay content that may be highly variable within a production field. In addition, we assume that the influence of a RWC amendment on SOC quality (i.e., mineral-associated organic matter and thermal stability increased and C_{mic}-to-SOC decreased) increased the volume of coarse porosity.

5. Conclusions

Crop biomass production, grain yields and crop nutrients were assessed during a five year period after a single RWC amendment. A set of soil biological, physical and chemical properties were investigated at the end of the 5-year experimental crop sequence. Grain yields and crop biomass production were not affected by the RWC amendment. The observed increase in macronutrient availability for the 2nd and the 3rd crop after RWC amendment suggests that it could be a sustainable alternative to the use of N and P fertilizers. Further research is necessary to quantify N and P use efficiency of RWC. In addition, the decrease of micro-nutrient availability in the second half of the study period highlights the need to investigate the relationships between RWC decomposition and micronutrient availability. Studies on whether (and in what pedoclimatic conditions) repeated amendments can lead to micronutrient deficiency in crops would be of great interest for future recommendations.

The large part of C mineralized from the RWC amendment suggests that the latter promoted biological activity. Furthermore, RWC increased SOC in a stabilized form after 5 years in soils with low SOC-to-clay ratio (7.6%). Therefore, RWC represents a promising option for SOC storage in soils. The improvement in chemical and physical soil quality, partly due to a RWC amendment, was linearly related to the increase in SOC content. We found the RWC amendment affected SOC quality, which is assumed to have improved soil structural porosity and, in turn, easily available water storage and aeration. The use of RWC is therefore recommended in the context of climate change mitigation as it has potential to improve drought resistance in crops and to increase storage of C from the atmosphere as an on-farm produced manure. More studies are necessary to quantify the potential of RWC to improve soil fertility and C storage, particularly in the long-term and across contrasted soil and site conditions (see Fig. 4).

CRediT authorship contribution statement

Mario Fontana: Conceptualization, Methodology, Data curation, Investigation, Visualization, Formal analysis, Writing – original draft. **Alice Johannes:** Methodology, Data curation, Writing – review & editing. **Claudio Zaccone:** Methodology, Investigation, Writing – review & editing. **Peter Weisskopf:** Review & editing. **Thomas Guillaume:** Review & editing. **Luca Bragazza:** Review & editing. **Saïd Elfouki:** Investigation, Formal analysis. **Raphael Charles:** Review & editing. **Sokrat Sinaj:** Project administration, Funding acquisition, Resources, Conceptualization, Methodology, Writing – review & editing.

Declaration of 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.

Data availability

Data will be made available on request

Acknowledgment

Funding were provided by Agroscope.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.eti.2023.103143.

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