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ORIGINAL PAPER

Shoot and Root Decomposition from Different Cropping Systems Under Semiarid Mediterranean Conditions

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Abstract

Improving the management of crop residues is essential for water and soil conservation and for increasing soil carbon (C) and nitrogen (N) levels in dryland agroecosystems. The main objective of the study was to evaluate the decomposition dynamics and C and N released from crop residues from different cropping systems under semiarid Mediterranean conditions. A litterbag experiment was conducted from July of 2020 to June of 2021 to examine the shoot and root decomposition dynamics of different cropping systems; the following systems were selected: V(B), vetch (*Vicia sativa*) residue decomposition in a barley crop; B(V), barley (*Hordeum vulgare L.*) residue decomposition in a vetch crop; P(B), pea (*Pisum sativum*) residue decomposition in a barley crop; B(P), barley residue decomposition in a pea crop; and B(B), barley residue decomposition in a barley crop. After 48 weeks of decomposition, a 45% and 60% of residues mass remaining (MR) was found corresponding to vetch and pea shoot residues respectively, whilst barley MR ranged 77–87% depending on the cropping system. In root residues, the mass decay from legume residues (40–45%) was higher compared to barley residues (17–29%). Exponential decay and linear models explained the residue decomposition observed in our study conditions. Residues C to N ratio and edaphoclimatic conditions played a major role controlling the decomposition. Residue decomposition and C and N release dynamics from different crop residues need to be considered for a transition to more sustainable agroecosystems under Mediterranean semiarid conditions.

Keywords Decay exponential model · Dryland agroecosystems · Crop residues · Legumes · Barley · Crop rotations

Abbreviations

B(B)	Barley residue decomposition in a barley crop
B(P)	Barley residue decomposition in a pea crop
B(V)	Barley residue decomposition in a vetch crop
BG	β-Glucosidase soil activity
CR	Carbon remaining in the residues
MBC	Microbial biomass carbon
MR	Mass remaining in the residues
NH_4^+	Soil ammonium content
NO_3^-	Soil nitrate content
NR	Nitrogen remaining in the residues
P(B)	Pea residue decomposition in a barley crop
POXC	Permanganate oxidizable labile carbon
TC	Soil temperature
V(B)	Vetch residue decomposition in a barley crop
VWC	Soil volumetric water content

1 Introduction

Optimizing the management of crop residues after harvest is fundamental for soil and water conservation as well as maintaining adequate soil organic matter (SOM) levels (Reicosky and Wilts 2005). In Mediterranean semiarid areas, water scarcity limits crop production resulting in low SOM contents, poor soil quality, and weak structure (López et al. 2005). Besides the severe edaphoclimatic conditions, traditional farming practices such as intensive tillage and crop residues removal increase the susceptibility of drylands to

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land degradation (López et al. 2000). A better understanding of crop residue decomposition and its subsequent C and N released is a key to design agricultural practices for improving the sustainability of these dryland agroecosystems. The NE Spain, with a typical semiarid Mediterranean climate, is characterized by high frequency of erosive wind episodes throughout the year (López et al. 2005). In this region, cropping systems are mainly based on winter cereals, usually presenting low crop diversity, being the most common the traditional cereal-fallow rotation associated with intensive tillage.

Crop diversification and conservation tillage have been proposed as sustainable agricultural practices with a positive impact on dryland agrosystems (Arrúe et al. 2019); these practices imply a crop residue cover that contributes to the maintenance of soil moisture and, as a consequence, the build-up of soil nutrients from decomposition. During the summer fallow, covering the soil with crop residues is a key strategy to reduce soil and water losses in Mediterranean agroecosystems (López et al. 2005). Cover crops and crop rotations lead to an increase of the residue returned to the soil (Kuo et al. 1997), efficiently providing nutrients for successive crops. In comparison with monoculture, more diversified cropping systems produce greater types of crop residues that may alter the C and N soil dynamics through their decompositions (Ranells and Wagger 1996). Legumes are considered an important N source due to its ability for establishing symbiotic associations with microorganisms; consequently, its introduction in cropping systems may improve soil fertility and crop yields (Kebede 2021; Papastylianou 1990). Ranells and Wagger (1996) observed greater decomposition rates in a grass-legume rotation than under a grass monoculture system. In a soil incubation system, McDaniel et al. (2014) reported higher microbial activity in complex crop rotations including legumes compared to the cropping system only based on cereals. The higher microbial diversity in the diversificated systems contributed to accelerate the decomposition of low-quality residues by a higher N retention in microbial biomass. Nevertheless, the successful presence of legume crops or its introduction in crop rotations is still low in rainfed semiarid conditions (Cooper et al. 1987) due to their low productivity compared to winter cereals and a more complex management associated to higher costs (Díaz-Ambrona and Mínguez 2001).

At field scale, returning the residues to the soil through a surface cover or its incorporation into the soil highly influences the decomposition rates by the exposition level to the environmental conditions. In drylands, precipitation and temperature abrupt fluctuations entail that crop residues left over the soil have longer persistence than incorporated residues (Douglas et al. 1980), which translates into slower decomposition rates of residues aboveground compared to belowground. Besides, residue decomposition and nutrient dynamics are also affected by the chemical composition of the residue (Johnson et al. 2007; Stubbs et al. 2009), the amount, placement and distribution of the residues (Angers and Recous 1997), and the crop species (Burgess et al. 2002; Jahanzad et al. 2016; Sievers and Cook 2018). Low C:N ratio has being proven to be an important driver of residue decomposition (Jahanzad et al. 2016; Jani et al. 2016; Ordóñez-Fernández et al. 2007; Sievers and Cook 2018). Due to the complexity of decomposition dynamics, several models have been discussed in order to estimate above and belowground mass decay over time under different environmental conditions (Harmon et al. 2009). The single exponential decay model, as proposed for Olson (1963), is still the most used to describe decomposition processes, although a low mass decay rate over time might be well explained by lineal model at least during the first or second year (Grigal and McColl 1977).

Under semiarid Mediterranean conditions, a better understanding of crop residue decomposition process and the release of C and N from the residues to the soil is essential for optimizing the equilibrium between residue maintenance and the residues' contribution to the soil C and N pool from different cropping systems. Despite the valuable information that can be extracted from studying decomposition dynamics, a low number of studies are available in diversified Mediterranean crops in rainfed conditions (Arrúe et al. 2019). Accordingly, the aim of the study was to evaluate residue decomposition dynamics and its contribution to release C and N to the soil in different cropping systems under Mediterranean semiarid conditions. Our hypothesis was that more diversified cropping systems may favor the optimization of nutrients' release rates through decomposition for enhancing soil functioning, which may benefit the following crops. However, for taking the maximum advantage that entails crop residue decomposition, crop growth and development should be adequate under semiarid Mediterranean conditions. The specific objectives were (1) comparing single exponential decay model and lineal model fittings in order to describe the decomposition process of different part plants and crop species; (2) quantifying mass decomposition and C and N decay rates of roots and shoots residues from different cropping systems; and (3) assessing the effect of the cropping system on the soil through the crop residue decomposition under semiarid Mediterranean conditions.

2 Materials and Methods

2.1 Site Conditions and Experimental Design

The experimental site was located at a dryland research field of the Aula Dei Experimental Station (EEAD-CSIC), Zaragoza, Spain (41° 44′ 21.7″ N, 0° 46′ 40.5″ W, 255m altitude) in NE Spain. The area is characterized by a Mediterranean semiarid climate with 339.2 mm of mean annual rainfall, an air average temperature of 14.6 °C, a maximum of 28.1 °C, and 2.4 °C of minimum average temperature. Mean air temperature and annual mean precipitation of the area was calculated based on agroclimatic data collected from the Irrigation Agroclimatic Information System (SIAR in Spanish), a weather network of Spain.

The soil is a Typic Calcixerept (fine-loamy, mixed, calcareous, thermic) according to the USDA soil classification (Soil Survey Staff, 2014). The soil water-holding capacity was 158 mm at the first 80 cm of depth. The Ap horizon (0–40 cm) properties were as follows: bulk density, 1.34 g cm^{-3}; soil organic carbon, 8.1 g kg^{-1}; pH (H_2O, soil, 1:2.5), 8.0; electrical conductivity (1:5), 1.97 dS m^{-1}; $CaCO_3$ eq. (%), 39.6; and loam texture being sand (2000–50 μm), silt (50–2 μm), and clay (< 2 μm) content: 211, 588, and 201 g kg^{-1}, respectively.

The plots selected for this study are part of an experiment established in 2018 in which different cropping systems along with conservation and conventional tillage practices are compared in semiarid rainfed Mediterranean conditions. For this study, the next cropping systems were considered: a continuous barley monoculture system, B (B), and two crop rotations, including both crop phases; vetch followed by barley, V(B); barley followed by vetch, B(V); pea followed by barley, P(B); and barley followed by pea, B (P). The field was arranged in a randomized complete block design, with three replicates. The plot area was 6 by 50 m. All cropping systems were under no-tillage.

Nitrogen fertilizer was only applied in barley at a rate of 20 kg N ha^{-1} of a NPK complex (8% N- N-NH_4^+ – 15% P_2O_5–15 K_2O) before sowing (October) and 40 kg N ha^{-1} of calcium ammonium nitrate N-27% (13.5% of N-NH_4^+ and – 13.5% of N-NO_3^-) as topdressing in spring. For legume crops, a no-nitrogen fertilizer was applied at a rate 37.5 kg P ha^{-1} of PK complex (10% P_2O_5 and 16% K_2O) before planting. After harvest, the crop biomass was chopped and spread over the soil.

2.2 Biomass Collection and Litterbags

Plant material was collected during the harvest of the 2019–2020 season (in spring 2020). The plant material collected was shoot mass from aboveground and root mass from belowground of the next crop species: barley, pea, and vetch. Pea residues were collected from another experimental field due to the poor crop growth in 2020. Root biomass was previously distilled water-rinsed to eliminate soil particles and oven-dried at a 60°C during 24 h. Shoot biomass was directly oven-dried at a 60 °C during 48 h. The purpose of oven-drying the plant samples was its adequate preservation since its collection until the experimental set up (mid-July). The samples were cut into smaller pieces and mixed ensuring a proper homogenization according to species (barley, vetch, and pea) and type of residue (shoot and root).

The litterbags were made of 2-mm nylon mesh of 30 cm by 12 cm using a heat-sealing machine. However, legume shoots and roots samples of all treatments were placed in a double mesh-bag for avoiding biomass loss due to their easy fragmentation. Firstly, samples were introduced in fabric mesh-bags of 10 by 15 cm (legume shoots) and 7 by 9 cm (root). After, these fabric mesh-bags containing the samples were placed in the nylon litterbags: 30 by 12 cm (legume shoot) and 10 by 10 cm (roots). Litterbags containing barley shoots were filled with 10g, whilst for vetch and pea shoots, litterbags were filled with 5g. These specific amounts for the litterbags were established based on the amount of shoot residues, generated by the previous growing crops, available over the soil surface. Conversely, root biomass litterbags for all treatments (vetch, pea, and barley) were filled only with one gram due to the difficulty of extracting roots from the soil in adequate conditions.

The litterbags containing shoot biomass were installed on the surface whereas litterbags with root residues were inserted 10 cm of soil depth. There were two replicates for each plot, type of plant material, and sampling time. A total of 32 litterbags per plot, 16 of shoot and 16 of root biomass, were positioned in the field. Litterbags were installed in summer fallow (July 2020). In October 2020, litterbags were carefully removed and placed back after sowing. Barley litterbags were placed into the plots in which barley was grown in the previous cropping season: B(V), B(P), and B(B). Vetch and pea litterbags were inserted into the plots in which vetch and pea were grown during the previous cropping season: V(B) and P(B), respectively.

2.3 Crop Residues and Soil Samplings and Analyses

Litterbags sampling were processed at 0 (15/07/2020), 3 (04/08/2020), 6 (25/08/2020), 9 (15/09/2020), 14 (19/10/2020), 25 (07/01/2021), 39 (15/04/2021), and 48 (15/06/2021) weeks after the installation. Since the crops established in our field trial were annual crops, the experiment duration was carried out during the following growing season, starting at the moment of the previous harvest, when residues were left over the soil. Our goal was to study the decomposition of the residues from a specific growing season under different cropping systems overall the next season.

At each sampling time, two litterbags of each plant part were collected from each plot and transported to the laboratory for being processed. Shoot biomass retrieved from litterbags was carefully brush-cleaned to eliminate soil particles and oven-dried 60°C during 48h, whilst root mass samples, after being brushed, were oven-dried 60°C during 24h. During July to September 2020, all samples were brushed-cleaned and oven-dried. Further on, root samples required a previous wash to ensure no soil contamination. In particular, root samples were washed using a sodium hexametaphosphate solution (5%) during 20 h and next samples were distilled water-rinsed and subsequently oven-dried 60°C during 24h. Dry weights of shoot and root biomass were measured.

All plant samples from week 9 to 48 were grounded to pass through 1-mm mesh and analyzed by dry combustion for determining C and N content (Elemental Analyzer LECO TruSpec). Due to a processing error, % C and % N data of root samples from weeks 3, 6, and 9 was not measured. To correct for possible soil contamination, samples were ashed at 500 °C for 5 h and then the weight of ash was subtracted from the dry sample weight. At the beginning of the assay, subsamples of each different specie and both plant parts were taken for determining the initial chemical composition of the residues: lignin, acid detergent fiber, and neutral detergent fiber contents. Initial cellulose content was determined by subtracting lignin from acid detergent fiber and hemicellulose content by subtracting acid detergent fiber from neutral detergent fiber (Sievers and Cook 2018).

Moreover, at each sampling event, a composite soil sample was taken beside the litterbags from the 0–10 cm soil layer in two sites per plot. Each soil sample was divided in two subsamples. Soil ammonium and nitrate concentrations were quantified through an extraction, consisting of 20g of fresh soil with 100 mL of KCl (2M). The extracts were frozen and later analyzed. NH_4^+ content was determined by salicylate method (Kempers and Zweers 1986). NO_3^- content was determined by UV-spectrophotometry (MAPA 1986). The rest of the soil sample was carefully 2-mm sieved, air-dried, and stored at room temperature until analyses. Permanganate oxidizable carbon (POXC) determination was measured as described in Lucas and Weil (2012). β-glucosidase activity was analyzed in soil air-dried samples (Zornoza et al. 2006) by ρ-nitrophenol determination (Tabatabai 1982). Microbial biomass C (MBC) was assayed through a glucose-induced respiration, consisting of rewetting 5 g of soil with a solution of glucose at 40% soil water-holding capacity, and subsequently quantified by monitoring the CO_2 production at 20°C for 24 h using the μ-Trac 4200 system (SY-LAB, GmbH P.O. Box 47, A-3002 Pukersdorf, Austria). This system is a thermostatizated incubator block based on the variation of electrical impedance of a KOH^- 0.2% water solution.

In each sampling date, the soil temperature was measured at 10 cm depth using a probe Crison TM 65 (Carpi, Italy). Moisture content was assayed by the gravimetric method, drying a soil sample at 105 °C during 24 h. Soil bulk density was measured once per month by the cylinder method (Grossman and Reinsch 2002). Volumetric water content of the soil was calculated from gravimetric moisture content and bulk density.

2.4 Data Analysis

The percentage of ash-free mass remaining (MR, %) at any given time (weeks) was calculated as:

$$MR = 100\ x\ (X_t/X_0) \tag{1}$$

where the Xt was the mass at each time (t) and X_0 was the initial mass at week 0. The percentage of nitrogen remaining NR (%) and carbon remaining CR (%) were calculated with same formula considering the MR (%) and N and C content at each given time.

Decomposition curves for buried and surface residues of each crop over a 48-week period were fitted to a simple negative exponential model and compared to a linear regression. The general form of the equation was:

$$MR = ae^{-kt} \tag{2}$$

where MR is the percentage of MR at any time (t), a is the y-intercept, and k is the decomposition decay rate.

The data was fitted with a single two-parameter exponential decay curve and a standard linear curve. The effect of treatment was evaluated in the estimated parameters in both models fitted using an ANOVA test. All soil parameters were also tested using a two-way ANOVA, weeks and treatment as main factors, and block as a random factor. The ANOVA assumptions were previously tested in the model residues; Levene test was used for the homogeneity of variances and Shapiro–Wilk for testing the normality. Some soil parameters required a data transformation in order to meet the ANOVA assumptions. A logarithmic transformation was necessary for MBC and a square root for POXC, NO_3^-, and soil temperature in order to meet the ANOVA assumptions. Effects were considered significant at $p \leq 0.05$ by the F test, and when the F test was significant, Tukey test was used for mean separations. A Pearson correlation matrix was performed to establish the relationships between the mass, the residues CR and NR, and all soil properties analyzed. All statistics and graphs were performed using R software version 2022.2.3.492 (Rstudio 2022).

3 Results

3.1 Weather Conditions

The daily air average temperature and precipitation registered during the experimental period (15th of July 2020 to 15th of June 2021) are presented in Fig. 1. A 14.5 °C and 263.2 mm were the air average temperature and total precipitation overall experimental period.

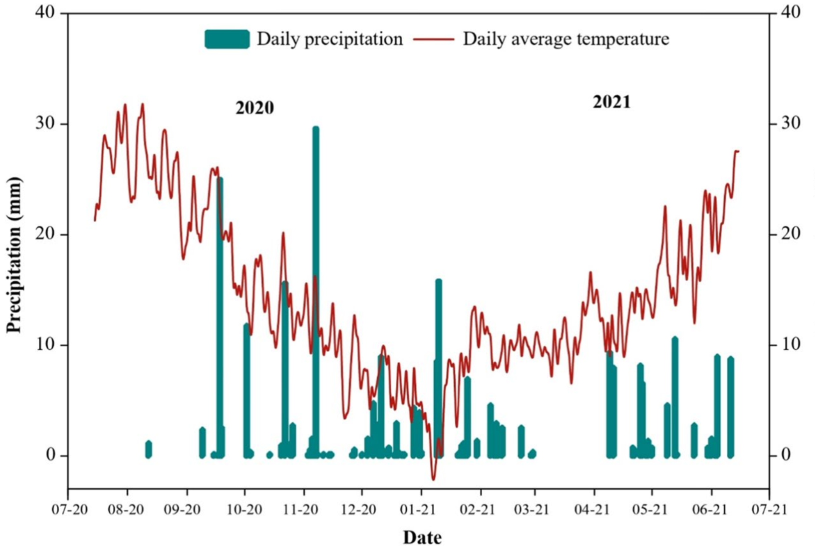


Fig. 1 Daily precipitation and air average temperature during the experimental period from 15th of July 2020 to 15th of June 2021 at the dryland research field

In 2020, summer months presented the highest average temperature values (25–27 °C) along with a limited precipitation (1.2 mm). The late summer and autumn months (September–November) were characterized by mild temperatures (10–20 °C) and presented approximately 97 mm of cumulative rainfall. Winter months (December–March) were cold (6–10 °C) with 89 mm of cumulative precipitation, approximately. In 2021, spring months (March–May) presented intermediate temperature values (13–23 °C) and moderate precipitation (76 mm, approximately) (Fig. 1).

3.2 Crop Residue Decomposition

Initial plant residue characterization is presented in Table 1. Pea and vetch residues showed a lower initial C to N ratio for both shoot and root residues. Barley residues presented higher contents of fiber (1307.3g kg^{-1}) and cellulose (445.6 g kg^{-1}) in its shoot biomass. Root biomass in barley, pea, and vetch presented about 51.8%, 51%, and 43.3% higher lignin content than in shoot residues, respectively. Hemicellulose was 8.2%, 20.5, and 28% greater in roots of barley, pea, and vetch, respectively, in comparison with shoot residues (Table 1).

Shoot and root residues MR of all treatments were fitted to an exponential decay and a linear model. Model fitting results were an estimation of parameters (Table 2) and a graphical representation (Fig. 2). Both model fittings showed the same trend; the treatments based on legumes shoot and roots showed higher decomposition rates in comparison to barley residues (Fig. 2 and Table 2). However, decomposition for all residue types seemed to be better described by the exponential model, as observed in the estimated parameter result table and graphs (Table 2 and Fig. 2). Despite the similar correlation coefficients (R^2) found between both fitted models, the lower RMSE values in the exponential decay model compared to the linear model in shoots and roots and in all treatments indicated that, in our study, the first model explained better the residue decomposition (Table 2). In the case of roots, mass decay model presented also higher R^2 coefficients in legume residues. The similar correlation coefficients (R^2) found between both fitted models, the lower RMSE values in the mass decay model compared to the linear model in shoots and roots, and in all treatments indicated

Table 1 Initial chemical content of plant residues previously to decomposition. Mean ± standard deviation of the mean of carbon, nitrogen, C:N ratio (carbon:nitrogen), fiber, lignin, hemicellulose, and cellulose content of the crop residues. Residue type is shoot and root plant biomass and crop species are barley, pea, and vetch

Residue type	Crop species	Total carbon (g kg^{-1})	Total nitrogen (g kg^{-1})	C:N ratio	Fiber (g kg^{-1})	Lignin (g kg^{-1})	Hemicellulose (g kg^{-1})	Cellulose (g kg^{-1})
Barley	Shoot	45.7 ± 0.33	0.58 ± 0.19	85.1 ± 22.4	1307.3 ± 4.6	47.9 ± 0.29	320.3 ± 4.59	445.6 ± 4.15
Barley	Root	44.8 ± 0.87	0.88 ± 0.19	52.5 ± 8.81	903.9 ± 2.6	99.6 ± 1.13	348.9 ± 1.79	355.9 ± 1.44
Pea	Shoot	44.5 ± 0.24	1.91 ± 0.16	23.5 ± 2.54	635.2 ± 10.3	71.5 ± 1.90	147.2 ± 3.07	345.0 ± 3.40
Pea	Root	44.6 ± 0.39	1.89 ± 0.14	23.7 ± 1.99	785.9 ± 6.0	146.0 ± 2.29	185.1 ± 1.60	308.8 ± 4.44
Vetch	Shoot	43.5 ± 0.74	2.05 ± 0.41	21.1 ± 4.24	597.4 ± 13.7	81.2 ± 0.44	131.0 ± 4.40	304.0 ± 9.37
Vetch	Root	43.1 ± 0.65	1.85 ± 0.15	23.5 ± 2.05	815.5 ± 3.4	143.3 ± 0.36	181.8 ± 0.13	347.0 ± 2.52

Table 2 Parameter estimates for the exponential decay and linear models used to describe the mass remaining (MR) of barley, vetch, and pea crop over 48 weeks of residue decomposition. The plant residues were shoot and root biomass. The treatments are as follows: B(V) are barley residues decomposing in a vetch phase; V(B) are vetch residues decomposing in a barley phase; B(P) are barley residues decomposing in pea phase; P(B) are pea residues decomposing in a barley phase; B(B) are barley residues decomposing in a barley phase

Crop residues	Crop species	Plant part	†Exponential decay model				‡Linear model			
			a	k	§RMSE	¥R^2	a	k	RMSE	R^2
B(V)	Barley	Shoot	99.0 a	−0.0039 b*	3.22	0.75	98.8 ns	−0.349 b	5.78	0.75
V(B)	Vetch	Shoot	103.6 a	−0.0116 a	8.69	0.77	102.4 ns	−0.961 a	17.0	0.80
B(P)	Barley	Shoot	98.9 a	−0.0031 b	4.43	0.53	98.8 ns	−0.284 b	5.20	0.53
P(B)	Pea	Shoot	100.3 a	−0.0099 a	4.55	0.89	99.2 ns	−0.794 a	4.46	0.90
B(B)	Barley	Shoot	99.2 a	−0.0041 b	5.25	0.58	99.0 ns	−0.374 b	5.21	0.59
p-value		Shoot	$p < 0.05$	$p < 0.001$			$p > 0.05$	$p < 0.001$		
B(V)	Barley	Root	98.7 ns	−0.0047 b	5.55	0.63	98.4 a	−0.410 b	11.6	0.62
V(B)	Vetch	Root	96.8 ns	−0.0160 a	9.87	0.77	93.3 b	−1.102 a	13.1	0.70
B(P)	Barley	Root	97.8 ns	−0.0041 b	4.88	0.64	97.5 a	−0.359 b	9.63	0.63
P(B)	Pea	Root	98.4 ns	−0.0131 a	7.77	0.82	95.7 ab	−0.914 a	17.4	0.78
B(B)	Barley	Root	99.2 ns	−0.0067 b	10.2	0.52	98.8 a	−0.572 b	16.1	0.52
p-value		Root	$p > 0.05$	$p < 0.001$			$p < 0.01$	$p < 0.001$		

†Exponential decay model is $MR = ae^{-kt}$, where MR is the percent MR at time (t), a is the y-intercept, and k is the decomposition constant

‡Linear model is $MR = kt + a$, where MR is the percent of MR at time (t), k is the slope, and a is the y-intercept

*Lower letter cases indicate significant differences between treatments $p < 0.05$; *ns*, non-significant $p > 0.05$

§*RMSE*, root mean square error; ¥ R^2, correlation coefficient

that the mass decay explained better residue decomposition (Table 2). In the case of roots, mass decay model presented also higher R^2 coefficients in legume residues. The graphical fitting drawn by the MR quantified at each sampling and treatment described rather a curve (Fig. 2a and b) than a negative linear pattern of decay (Fig. 2c and d), which also supported the exponential model as the best option to explain generally the residue decomposition.

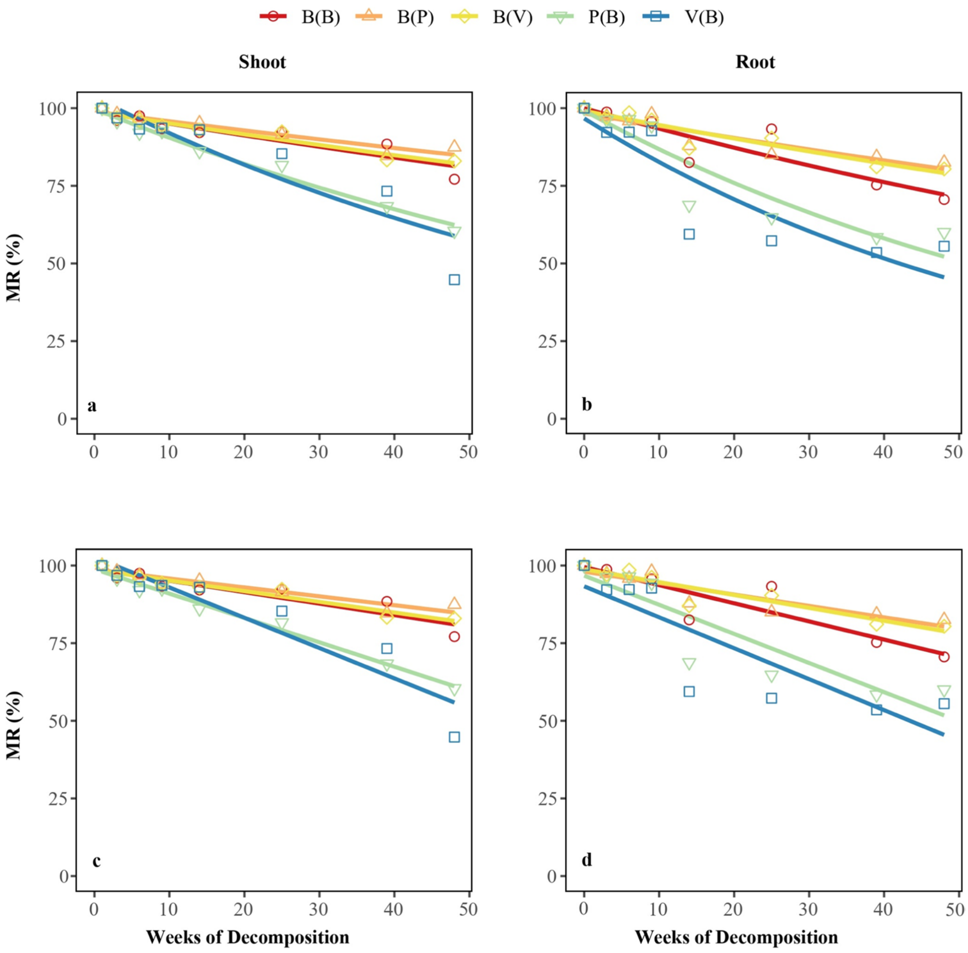
All crop residues showed steady decomposition rates during the first 6 weeks, but from week 9 onwards, the decomposition process started to be noticeable, especially in legume residues (Fig. 2). In general, shoots seemed to have had a more gradual decomposition than roots throughout the experimental period (Fig. 2 and Table 2). In the exponential decay model, the treatment had a significant effect on the decomposition rate (k), whilst in the linear model both estimated parameters (k, decomposition rate, and a, y-intercept) were affected by the treatment in shoot and root residues (Table 2). At the end of the experiment, V(B) and P(B) shoots showed a 55 and 40% of mass decay, whilst a 23, 17, and 13% were found in B(B), B(V), and B(P), respectively (Fig. 2). Meanwhile, root residues presented the most part of decomposition from week 9 to 14, moment when registered a sharp mass decay of 33, 26, 13, 10, and 9% in V(B), P(B), B(B), B(P), and B (V), respectively (Fig. 2). Similarly to shoots, legume residues presented the faster decomposition rate, with a 45% and 40% mass loss in V(B) and P(B), respectively, at the end of the experiment. Although barley residues were also characterized by a slow decomposition, in the case of root residues, B(B) presented a major mass loss (29%) compared to B(V) and B(P), with 20 and 17%, respectively (Fig. 2).

3.3 Carbon and Nitrogen Remaining in Crop Residues

The CR (Fig. 3) and NR (Fig. 4) of residues were also fitted graphically to both models. Slow C and N release rates from the residues to the soil were registered during the first 9 weeks of decomposition. A general rapid drop in V(B) and P(B) at week 14 was observed, contrarily to B(V), B(P), and B(B), where the C was gradually released (Fig. 3). At week 48, a 78% of V(B) and 64% of P(B) of C released from the shoot residues was recorded, whilst in barley treatments were found a 55, 54, and 50% B(B), B(P), and B(V), respectively (Fig. 3a and c). Roots showed an abrupt drop of CR from week 9 to 14 (Fig. 3b and d). After 48 weeks of decomposition, B(B) root residues reported the minor CR (48%), which was followed by V(B) and P(B), both with approximately 53% of CR; however, B(V) and B(P) residues showed 67–68% of C loss from the roots (Fig. 3).

Opposed to what was observed in C, the NR showed a decay trend over time only in legume residues from week 14 onwards, whereas barley residues reported no N released

Fig. 2 Percentage of mass remaining (MR) for shoot and root crop residues over 48 weeks of decomposition fitted to the mass decay and linear models: MR in shoot residues fitted to the mass decay model (**a**) and MR in root residues fitted to the mass decay model (**b**); MR in shoot residues fitted to the linear model (**c**) and MR in root residues fitted to the linear model (**d**). The treatments are as follows: V(B), vetch residue decomposition in a barley crop; B(V), barley residue decomposition in a vetch crop; P(B), pea residue decomposition in a barley crop; B(P), barley residue decomposition in a pea crop; and B(B), barley residue decomposition in a barley crop



from the residues or even an increase of its content in the last samplings; thus, V(B) and P(B) were better fitted by the decay curve compared to B(B), B(P), and B(V) (Fig. 4). Legume shoots gradually lost the NR (Fig. 4a and c), whereas roots released the major part of N at week 14 (Fig. 4b and d). At week 48, P(B) and V(B) shoot residues reported a 49 and 67% of NR, respectively. Regarding the root residues, the N released observed in P(B), B(B), and V(B) was 31, 33, and 38%, respectively (Fig. 4).

3.4 Soil Parameters and Its Correlation with MR, CR, and NR

In Table 3, the ANOVA results of all soil parameters studied are presented. Weeks of decomposition were significant for all soil parameters, whilst treatment was only significant for VWC, TC, MBC, NH_4^+, and NO_3^-. A significant interaction was found for TC, NH_4^+, and NO_3^-. Both treatments with legume residues showed significantly lower soil VWC compared to barley, whilst the soil TC was significantly lower in P(B) in regard to the other treatments; however, highest soil MBC was found in P(B), whereas the lowest in B(B) (Table 3). Soil NH_4 content was significantly higher in V(B) followed by P(B), contrarily to the treatments with barley residues, although soil NO_3^- content was only significantly higher in V(B) in respect to the rest of treatments (Table 3).

Soil moisture and temperature by treatment and sampling date are shown in Fig. 5. During weeks 0 to 6 (July–August), soil moisture was low (6–8%) accompanied by the highest range of soil temperatures (26–27 °C) over the entire experimental period. In weeks 9, 14, and 25 (September–January), an increase of soil moisture and a decrease of soil temperature trends were observed. From week 39 to 48 (April–June), soil moisture and soil temperature presented intermediate values, 9% and 25 °C, respectively. P(B) treatment presented the lowest soil temperature at week 0 (July), 14 (autumn), and 25 (winter) compared to the other treatments (Fig. 5).

Soil POXC, BG activity, and MBC corresponding to the plots where the residues were applied at each sampling during the experimental period are presented in Fig. 6. Soil POXC content showed an increase–decrease trend over the 48 weeks of decomposition (Fig. 6a). There was a noticeable increase in its content (around 180 to 400 mg POXC kg^{-1}) from week 0 to 9 (July–September), a decrease from week 9 to 25 (September–January), a less sharp increase from 25 to 39 (January–April), and finally a decrease from week

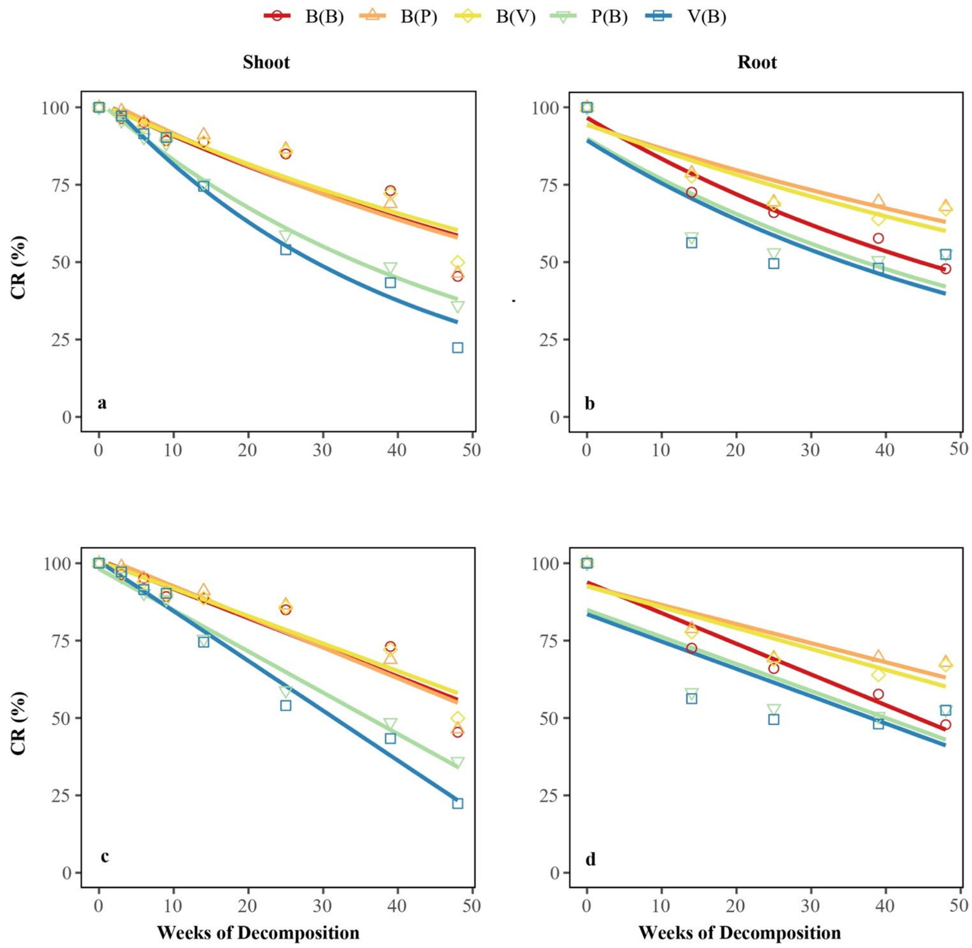


Fig. 3 Percentage of carbon (CR) for shoot and root residues, over 48 weeks of decomposition fitted to the mass decay and linear model: shoot CR fitted to the mass decay model (**a**), root CR fitted to the mass decay model (**b**), shoot CR fitted to the linear model (**c**), and root CR fitted to the linear model (**d**). The treatments are as follows: V(B), vetch residue decomposition in a barley phase; B(V), barley residue decomposition in a vetch phase; P(B), pea residue decomposition in a barley phase; B(P), barley residue decomposition in a pea phase; and B(B), barley residue decomposition in a barley phase

39 to 48 (April–June). However, soil BG activity showed an abrupt first decrease trend from week 0 to 3 (July–early August), although the rest of the experimental period had an increase trend until the end of the experiment, which was observed in two periods of increment: between treatments $p < 0.05$ (June) (Fig. 6b). Regarding the soil MBC pattern over time, three periods of increase trend were observed: weeks 0 to 3 (July–early August), 6 to 14 (late–August to October), and 25 to 48 (January–June) (Fig. 6c).

With regard to soil NO_3^- and NH_4^+ contents over the 48 weeks of decomposition, from weeks 0 to 14, a general increment trend was observed for NO_3^- (Fig. 7a), whereas NH_4 pattern over time was more irregular between different treatments (Fig. 7b). V(B) treatment not only showed significantly higher soil NO_3^- and NH_4^+ contents in several sampling dates comparing to the other treatments, but also was the treatment that registered the highest concentration peaks (Figs. 7a and b). Soil NO_3^- content had a clear decrease from week 14 to 48 (October–June), whilst at week 48, NH_4^+ had a sharp increase of its content in the soil in all treatments.

The correlation coefficients found between MR, CR, NR, and all soil parameters analyzed in shoot and root residues are shown in Table 4. In shoot residues, MR and CR were correlated negatively with BG and VWC and positively with TC and POXC, whilst NR was negatively correlated with VWC and NO_3^- and positively with TC, MBC, and NH_4^+. However, for roots residues, MR, CR, and NR presented a positive relationship with TC, whereas VWC was correlated negatively only with MR and CR. BG activity was negatively correlated with MR and MBC positively with CR of the root residues (Table 4).

4 Discussion

In Mediterranean semiarid conditions, the crop decomposition and C and N release from the residues dynamics were impacted by the crop specie (barley, pea, and vetch), the type of plant residue (shoot, root), and also for the temporal variability, with periods of negative or positive environmental conditions for decomposition.

Residue decomposition and, thus, C and N release patterns can be partially explained from the seasonal climate conditions. From week 0 to 6, residue decomposition was limited due to the drought and elevated temperatures of

Fig. 4 Percentage of nitrogen (NR) for shoot and root residues over 48 weeks of decomposition fitted to the mass decay and linear model: shoot NR fitted to the mass decay model (**a**), root NR fitted to the mass decay model (**b**), shoot NR fitted to the linear model (**c**), and root NR fitted to the linear model (**d**). The treatments are as follows: V(B), vetch residue decomposition in a barley phase; B(V), barley residue decomposition in a vetch phase; P(B), pea residue decomposition in a barley phase; B(P), barley residue decomposition in a pea phase; and B(B), barley residue decomposition in a barley phase

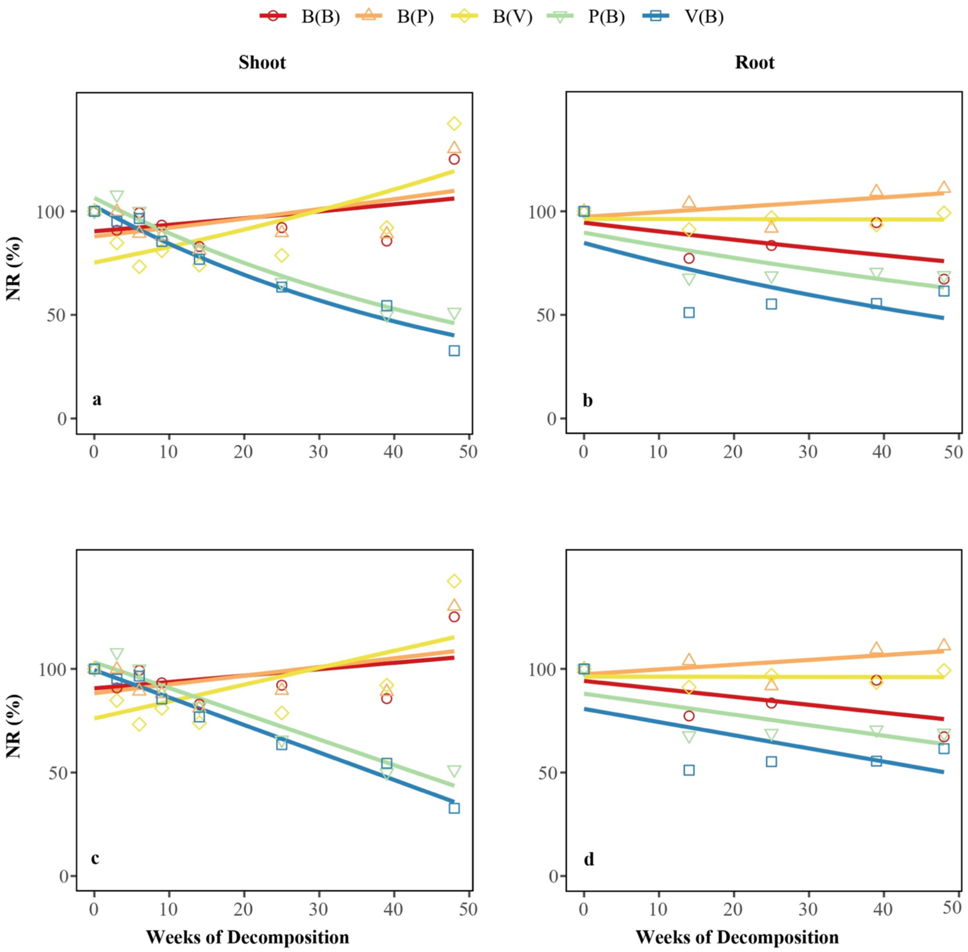


Table 3 Two-way analysis of variance (ANOVA) of all soil parameters measured (at 0–10 cm of soil depth) and its means of each treatment. The treatments are as follows: B(V) are barley residues decomposing in a vetch phase; V(B) are vetch residues decomposing in a barley phase; B(P) are barley residues decomposing in pea phase; P(B) are pea residues decomposing in a barley phase; B(B) are barley residues decomposing in a barley phase

	Soil parameters						
	[¥]VWC	TC	POXC	BG	MBC	NH_4^+	NO_3^-
Effects	*p*-values ($p < 0.05$)						
Treatment (T)	< 0.001	< 0.001	ns	ns	< 0.01	< 0.001	< 0.001
Weeks (W)	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001
T × W	ns[*]	< 0.001	ns	ns	ns	< 0.001	< 0.001
Treatment effects	Mean						
B(V)	12.4 a[*]	19.3 a	279.1 ns	0.620 ns	517.6 ab	2.71 c	18.2 b
V(B)	11.0 b	19.1 a	265.7 ns	0.528 ns	531.4 ab	3.87 a	53.1 a
B(P)	12.3 a	19.2 a	279.7 ns	0.551 ns	530.9 ab	2.70 c	19.7 b
P(B)	10.9 b	18.8 b	273.8 ns	0.551 ns	593.1 a	3.16 b	23.7 b
B(B)	12.6 a	19.0 a	265.3 ns	0.513 ns	474.2 b	2.66 c	17.8 b

[¥] *VWC*, soil volumetric water content; *TC*, soil temperature; *POXC*, soil permanganate oxidizable carbon; *BG*, soil β-glucosidase activity; *MBC*, microbial biomass carbon; NH_4^+, soil ammonium and NO_3^- nitrate contents, respectively

[*] *ns*, non-significant $p > 0.05$; lower letter cases indicate significant differences between treatments $p < 0.05$

summer, typical from Mediterranean. At the early stages of residue decomposition, fluctuations in temperature and moisture regimes have a greater influence on mass-loss than litter quality (Berg and Mcclaugherty 2003). In a semiarid dryland agroecosystem, Douglas et al. (1980) pointed out soil moisture as a limiting factor for straw residue decomposition during summer months. In our data, the negative relationships found between soil VWC and shoot and roots

Fig. 5 Soil moisture (**a**) expressed as volumetric water content, VWC, and soil temperature, TC (**b**), at each sampling date and treatment over 48 weeks of decomposition for each cropping system: V(B), vetch residues in a barley phase; B(V), barley residues in a vetch phase; P(B), pea residues in a barley phase; B(P), barley residues in a pea phase; and B(B), barley residues in a barley phase

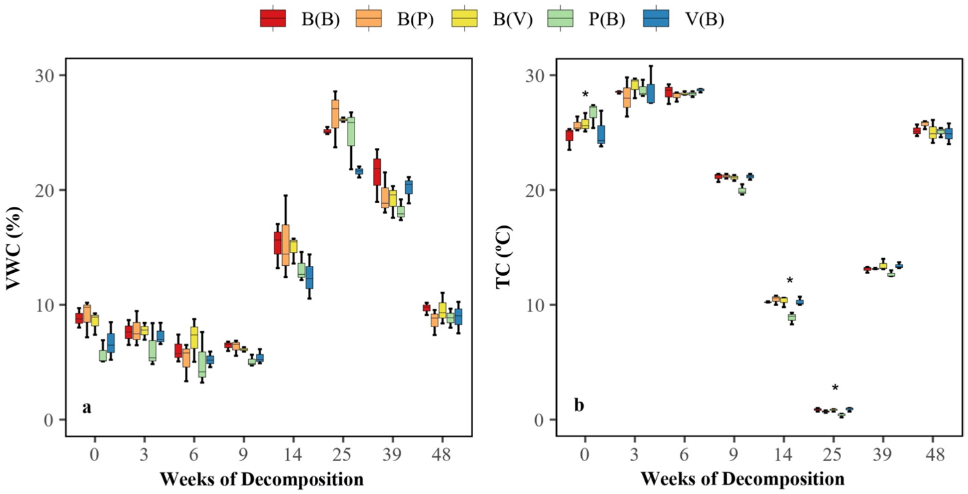
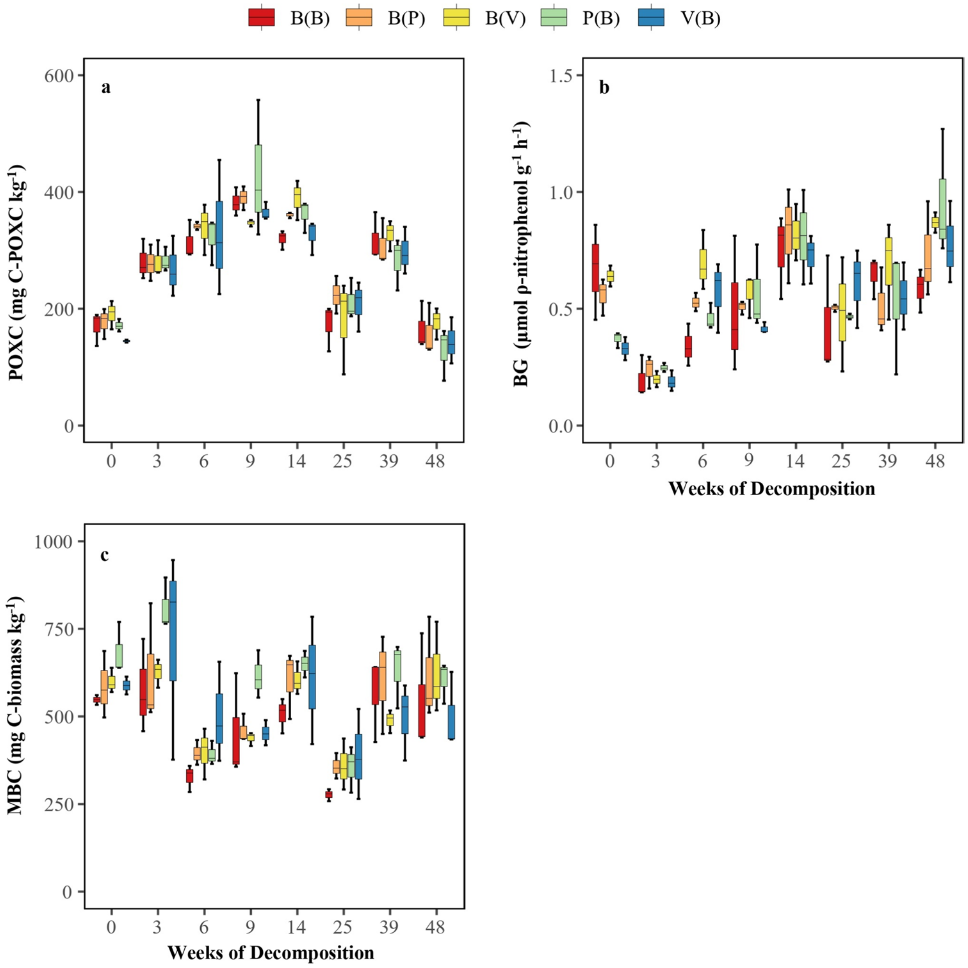


Fig. 6 Soil permanganate oxidizable carbon content, POXC (**a**), β-glucosidase soil activity, BG (**b**), and soil microbial biomass, MBC (**c**), over 48 weeks of experiment for each cropping system: V(B), vetch residues in a barley phase; B(V), barley residues in a vetch phase; P(B), pea residues in a barley phase; B(P), barley residues in a pea phase; and B(B), barley residues in a barley phase



MR also indicated that the availability of soil water is the main driver of decomposition in our conditions. From week 9 onwards (late September), residue decomposition and its C and N released from the residues started to be noticeable at a different rates depending on the type of residue (shoot or root) and the crop specie. The change in the dynamics may be attributed to the increase in the soil biological activity. From week 0 to 9, the increase observed in soil POXC was probably related with the accumulation of crop residues over soil surface associated to the no-tillage. Since BG is

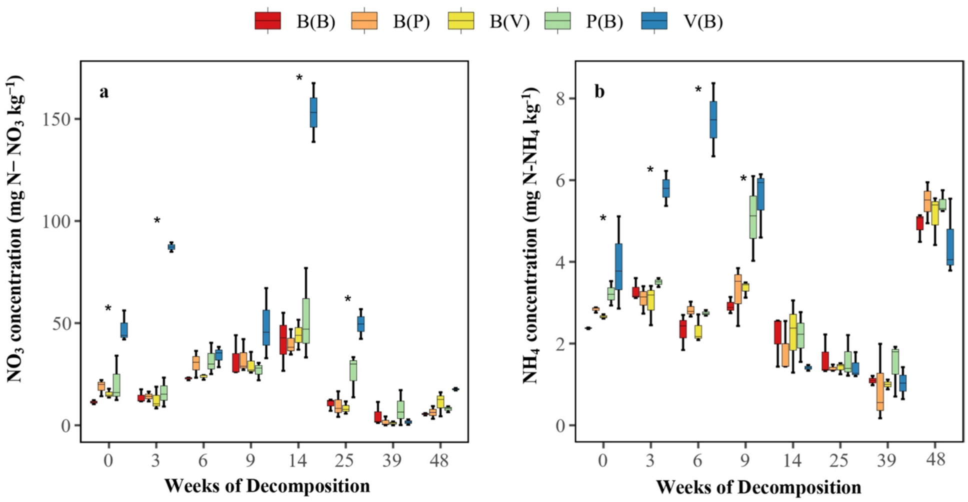


Fig. 7 Soil nitrate concentration, NO_3^- (**a**), and soil ammonium concentration, NH_4^+ (**b**), over 48 weeks of experiment for each cropping system: V(B), vetch residues in a barley phase; B(V), barley residues in a vetch phase; P(B), pea residues in a barley phase; B(P), barley residues in a pea phase; and B(B), barley residues in a barley phase

Table 4 Pearson correlation coefficients (R^2) for relationships between different soil parameters, mass (MR), carbon (CR), and nitrogen remaining (NR) in the shoot and root residues

Soil parameters	Shoot			Root		
	MR[¥]	CR	NR	MR	CR	NR
VWC[§]	−0.27**	−0.36***	−0.32***	−0.50***	−0.49***	−0.21
TC	0.17	0.24**	0.35***	0.44***	0.43***	0.29*
POXC	0.21*	0.30**	−0.18	0.10	−0.21	−0.13
BG	−0.31***	−0.39***	−0.02	−0.39***	−0.16	0.22
MBC	0.02	0.02	0.19*	0.06	0.28*	0.17
NH_4^+	−0.09	−0.12	0.23*	0.09	0.01	0.00
NO_3^-	−0.03	0.02	−0.19*	−0.09	−0.02	−0.23

*, **, and *** indicate significance at $p < 0.05$, $p < 0.01$, and $p < 0.001$, respectively

[§] *VWC*, soil volumetric water content; *TC*, soil temperature; *POXC*, permanganate oxidizable carbon; *BG*, β-glucosidase enzyme activity; *MBC*, microbial biomass carbon; *NH_4^+*, soil ammonium content; *NO_3^-*, soil nitrate content

the major degrading cellulose enzyme, its soil activity can be a good indicator of the decomposition process (Shukla and Varma 2011). The fact that a drop of POXC coincided with an increase of the soil BG activity and VWC levels (week 9) supported that the decomposition was delayed until autumn when moderate temperatures and the availability of nutrients and water favored soil biological activity. Despite a great part of residue decomposition occurred in autumn, the noticeable shoot mass loss from week 39 to 48 in both barley and legumes could be explained by the increase of soil biological activity of spring. In semiarid Mediterranean conditions, Ordóñez-Fernández et al. (2007) attributed the estimated mass loss of pea and sunflower (57 and 91%, respectively) to autumn rains and the mass loss of wheat (35%) to rains occurred in spring. In our study, despite the observed decrease of POXC, MBC, and BG activity during winter, decomposition of shoots did not seem to have been limited by the drop of temperatures, probably because air average temperature was 5–6°C higher than soil temperatures (0.7°C).

Shoot and root mass and the release of the CR and NR from the residues might be also explained by the level of contact between residues and soil particles. Residues incorporated into the soil have a greater surface area available for microbial degradation, thus accelerating decomposition and nutrient cycling rates; however, residues left on the soil surface are more exposed to fluctuating environmental conditions as well as a reduced contact with soil decomposers (Lupwayi et al. 2004). This could explain the first rapid decomposition of root MR, CR, and NR followed by a steady period compared to the more gradual decomposition of shoot residues. As microbes consume the more readily decomposable material, the chemical content of the residue becomes increasingly more recalcitrant (Johnson et al. 2007), which explains the similar mass and C decay rates observed from week 14 to 48 in root residues. Thereafter, the disappearance of the easily decomposable fraction, the steady decomposition, and slow C and N release rates from roots could be linked to the recalcitrant cell wall constituents, which probably remained in the residues (Lupwayi et al. 2004, 2006).

Residues from different crop species impacted the decomposition rates and its resulting C and N release to the soil. Several authors have linked the faster decomposition rates (Lupwayi et al. 2004; Ordóñez-Fernández et al. 2007; Sievers and Cook 2018) and C and N release (Jahanzad et al. 2016; Lupwayi et al. 2006; Ranells and Wagger 1996) of legumes with the lower C:N ratio compared with winter cereals. Our study results also found a clear trend of fast decomposition in legumes in regard to barley residues associated to lower C:N ratios under semiarid Mediterranean conditions. Besides, the fact that legume roots presented larger lignin content compared to barley supported that shoot and root decomposition were both mainly driven by C:N ratio, although the low decomposition rates observed in barley residues probably were also influenced by its initial high fiber content. In a study of similar duration, Lupwayi et al. (2004) reported approximately 75 and a 65% of mass loss in buried and surface clover residues, respectively, however, only 27% of barley surface mass decay in 52 weeks of decomposition. These faster decomposition rates determined that legumes described more clearly a decay curve than barley residues. In similar edaphoclimatic conditions to our study, Ordóñez-Fernández et al. (2007) reported a better fitting for pea than for wheat residue decomposition using a single exponential decay model. Contrarily to legumes, high C:N ratio of barley residues was associated with slow decomposition rates. Although in similar conditions to our study, Douglas et al. (1980) indicated that wheat straw decomposition was well described as a linear function over time associated to slow decomposition rates. However, in our study, the lower RMSE of the exponential decay model in all treatments and residues indicated a more adequate fitting, despite that the graphical fitting results were not as clear.

Regarding the CR and NR results, legumes seemed to have contributed to increase the soil NO_3^- and NH_4^+ contents due to their low C:N ratio, especially in shoots; also, their lower recalcitrant fraction (fibers, cellulose, and hemicellulose) in comparison to barley residues probably influenced the decomposition rates and, thus, C and N release from the residues. Lupwayi et al. (2006) estimated a 64% N released in zero tillage pea residues, a similar value to our 49 and 65% of N released in pea and vetch surface residues, respectively. However, our results indicated that barley residues N released to the soil were extremely low or inexistent over the 48 weeks of decomposition. Residues characterized by low N contents or a high C:N ratios are expected to result in microbial N immobilization (Johnson et al. 2007) due to a higher competition for the available N by microorganisms, consequently decreasing the decomposition and its nutrient release (Kumar and Goh 1999). Sievers and Cook (2018) concluded that cereal rye residues may immobilize N because of its high C:N ratio and decompose at a slow rate. Also, Lupwayi et al. (2006) reported an increase of NR in wheat residues under zero tillage that was attributed to microbial N immobilization. Since N is necessary for soil microorganisms in order to synthesize their cellular biomass, a high C dilutes the N concentration in crop residues (Lupwayi et al. 2006), reducing its decomposition rates. Then, in our study, N low availability associated to barley residues could have promoted a N-demand by soil microbiota, which supports microbial N-immobilization as a likely explanation for NR increase of barley shoots and B(V) roots in the last weeks of decomposition.

In our study, the cropping system influenced residue decomposition. For example, the significantly higher soil VWC associated to the plots with barley residues may explain the 6 and 10% more mass loss observed in B(B) shoots compared to B(V) and B(P). Since barley crops are well adapted to limited-water environments (Álvaro-Fuentes et al. 2009), an adequate growth and development of these crops are expected under Mediterranean semiarid areas. Maintaining a plant cover over the soil, either a growing crops or its resulting residues, can be interesting for preserving water and soil resources in Mediterranean agroecosystems (López et al. 2005), besides, buffering climatic fluctuations. Therefore, barley continuous monoculture, B(B), probably favored water preservation in comparison to the other cropping systems that had a diversified crop sequence. An accumulation of residues as a soil cover could have promoted the activity of decomposers and, thus, accelerated more the decomposition of barley residues in B(B) compared to B(V) and B(P).

Conversely, despite the legume phase, both crop rotations were less successful than the barley preserving soil moisture; their contribution to increase the soil N pool was significantly higher. The fact that the major part of legume residue decomposition was in autumn, linked to the first rains, gives an opportunity to reduce the N-fertilized application at moment of sowing (October). This can be a good strategy for increasing soil fertility and for reducing the need of external N inputs (Arrúe et al. 2019). The success of legume crops mainly depends on its adaptability to water-stress conditions and its water use efficiency (Álvaro-Fuentes et al. 2009). In our study, the vetch phase released more N than pea through decomposition due to a more adequate development of this crop in the study area. Thus, a barley-vetch rotation can be an interesting cropping system for improving the sustainability of Mediterranean semiarid agroecosystems. Likewise, further investigation is necessary for a better understanding of the cropping system effect on decomposition dynamics under Mediterranean semiarid agroecosystems.

5 Conclusions

In semiarid Mediterranean agroecosystems, the environmental conditions, crop species, and type of residue (shoot or root) had an impact on the decomposition and its associated nutrient release dynamics. Decay model represented legume decomposition well, whilst barley patterns were closer to a linear model. Under Mediterranean semiarid conditions, vetch could be a suitable candidate for introducing legumes in cropping systems based on winter-cereals due to its noticeable contribution to soil nitrogen pool through decomposition. Winter-cereal residues persistence on the soil also make cereal-legume crop rotations interesting for water and soil preservation. Our study highlights that the adoption of agriculture conservation practices has the potential for enhancing the soil functions and services through the presence of crop residues and their decomposition, and, thus, contributing to a major sustainability of drylands. However, under semiarid Mediterranean conditions, an adequate selection of crop species in the rotation is key for a successful adoption of diversified cropping systems that maximize an efficient nutrient release to the soil through the decomposition of crop residues.

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Data Availability The present study revealed that vetch rapid decomposition during summer months led to approximately a 30% ammonium increase, close to the sowing time. Its optimal growth and contribution to soil nitrogen pool suggest that vetch could be suitable candidate for introducing legumes in cropping systems based on winter-cereals under semiarid Mediterranean conditions.

Declarations

There is an existing preprint of the present research at available at Research Square. The reference is Martín-Brull I, Cantero-Martínez C, Franco-Luesma S, Lafuente MV, Álvaro-Fuentes J (2023), Shoot and root residue decomposition from different cropping systems under semiarid Mediterranean conditions. Preprint at Research Square. https://doi.org/10.21203/rs.3.rs-2468310/v1.

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