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Carbon sequestration potential of residues of different types of cover crops in olive groves under mediterranean climate

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Abstract

The maintenance of plant cover between olive grove lanes until the beginning of spring is a soil management alternative that is gradually being adopted by olive growers. As well as protecting the soil from erosion, plant covers have other advantages such as improving the physicochemical properties of the soil, favouring its biodiversity and contributing towards the capturing of atmospheric carbon and its fixation in the soil. A trial was conducted over three growing seasons in an olive plantation situated in southern Spain. It was designed to evaluate the C fixation potential of the residues of the cover species *Brachypodium distachyon*, *Eruca vesicaria*, *Sinapis alba* and of spontaneous weeds; and also to study the decomposition dynamics of plant residues after mowing cover. After 156 and 171 days of decomposition, the species that released the largest amount of C was *Brachypodium* with values of 2,157 and 1,666 kg ha^{-1} respectively, while the lowest values of 461 and 509 kg ha^{-1} were obtained by spontaneous weeds. During the third season (163 days of decomposition) and due to the weather conditions restricting the emergence and growth of cover, spontaneous weeds released the most C with a value of 1,494 kg ha^{-1} . With respect to the fixation of C, *Sinapis* records the best results with an increase in soil organic C (SOC) concentration of 7,690 kg ha^{-1} . Considering the three seasons and a depth of 20 cm, the behaviour sequence of the different species in favouring the fixation of soil organic C was *Sinapis* > *Brachypodium* > spontaneous weeds > *Eruca.*

Additional key words: carbon release; cover crops; soil carbon fixation.

Resumen

Potencial de secuestro de carbono de residuos de diferentes tipos de cubiertas en olivar bajo clima mediterráneo

El mantenimiento de una cubierta vegetal entre líneas de olivo hasta el comienzo de la primavera es una alternativa de manejo de suelo que está siendo gradualmente adoptada por los olivareros. Así como la protección del suelo contra la erosión, las cubiertas vegetales tienen otras ventajas como la mejora de las propiedades físico-químicas del suelo, favorecer su biodiversidad y contribuir a la captura de carbono atmosférico y su fijación en el suelo. Se ha realizado un ensayo durante tres campañas en una plantación de olivos situada en el sur de España. Éste fue diseñado para evaluar el potencial de fijación de C en residuos de cubiertas de las especies *Brachypodium distachyon*, *Eruca vesicaria*, *Sinapis alba* y de hierba espontánea; y también para estudiar la dinámica de descomposición del residuo tras el desbroce de la cubierta. Después de 156 y 171 días de descomposición, la especie que más cantidad de C liberó fue el *Brachypodium* con un valor de 2.157 y 1.666 kg ha^{-1} respectivamente, mientras que los valores más bajos fueron 461 y 509 kg ha^{-1} y se obtuvieron por la hierba espontánea. Durante la 3.ª campaña (163 días de descomposición), debido a las condiciones climáticas, se vio restringida la emergencia y el crecimiento de la cubierta. La hierba espontánea

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Abbreviations used: CEC (cation exchange capacity); $Cover_{max}$ (percentage of maximum cover along decomposition period); $Cover\ (\%)_{it}$ (percentage of cover obtained in the strip *i* and instant *t*); $Cover_t$ (percentage of cover at the instant *t*); M_t (residue mass at instant *t,* in kg ha^{-1}); OM (organic matter); SOC (soil organic carbon).

liberó la mayor cantidad de C con un valor de 1.494 kg ha^{-1}. Con respecto a la fijación de C, Sinapis registró los mejores resultados con un incremento de la concentración de C orgánico en suelo de 7.690 kg ha^{-1}. Considerando las 3 campañas y una profundidad de 20 cm, la secuencia de especies que favorecen la fijación de C orgánico fue *Sinapis* > > *Brachypodium* > hierba espontánea > *Eruca.*

Palabras clave adicionales: carbono liberado; cubierta vegetal; fijación de carbono en suelo.

Introduction

Tree crops in Spain occupy 4,748,283 ha or 46.5% of the total plantation surface of the area in 15 countries in Europe. The olive tree (*Olea europaea* L.) is the most common, representing 51% of the area, a figure that is increasing every year due to the lack of profitability of alternative crops. Mediterranean countries account for 98% of the world's olive cultivation area, largely in Spain (2.6 × 10^6 ha), Italy (1.4 × 10^6 ha), Greece (1 × 10^6 ha) and Portugal (0.5 × 10^6 ha). The European Common Agricultural Policy (CAP) budget devoted to olive groves amounts to 2,250 million euros (Beaufoy, 2002). Some 1.5 Mha of the 2.4 Mha olive groves registered in Spain are in Andalusia (MARM, 2010), accounting for over 80% of our production. These groves have traditionally occupied marginal, not very fertile soils broken up by erosion and steep slopes and are hardly suitable for other crops. Only in the last few decades areas with acceptable conditions of soil and climate started to be cultivated.

Currently, olive groves in Andalusia (Spain) suffer from environmental degradation, *i.e.* erosion, compaction and the risk of diffuse contamination, and also from the loss of soil fertility and the need to replenish the nutrients extracted by the plant or lost in erosion processes.

In order to mitigate this problem, research has been carried out since 1980 to facilitate weed control, improve soil management systems and prevent the mineralization of organic matter (OM) and the loss of soil structure. This has been done using no-till and the establishment of plant covers between the rows of olive trees to protect the soil from erosion (Francia *et al.*, 2006).

The benefits of plant covers recognized in the scientific and technological bibliography are very great: they reduce the pollution of surface waters (Rodríguez-Lizana *et al*., 2007), improve the water balance in the soil (Bowman & Billbrough, 2004), help to control weeds (Hatcher & Melander, 2003) and recycle the unused nitrogen in the soil (Weiner *et al*., 2002).

Historically, intensive tillage of agricultural land has caused substantial losses (from 30 to 50%) of C from the soil (Pulleman *et al.,* 2005). These C losses are due to the fragmentation of the soil triggered by tillage and facilitated by biological activity.

Loveland & Webb (2003), in a review of the critical levels of OM in agricultural soils of the temperate area, suggested that a C content of 1% could represent the threshold under which the functioning of the soil-crop system could be jeopardized even when adequate mineral fertilizers were added.

Covering the soil with a layer of stubble is a fundamental management practice in sustainable agriculture systems. The control of erosion, the accumulation of water in the profile and the maintenance of acceptable levels of OM and soil fertility are some of the aims of this practice. By conserving the resource, sustainable production over time is assured (Sparrow *et al*., 2006).

The development of this type of system requires knowledge of the quality and evolution of plant residues in order to set up management strategies. The quality of the residue is generally associated with two factors. On one hand, with the time it continues to protect the soil and on the other, its capacity to supply C as it decomposes, with the area's climate and the residue's composition being an influence on both aspects (Ernst *et al*., 2002). C represents approximately 50% of the dry weight of the harvest residues, hence its importance as a source of organic C to agricultural soils (Crovetto, 2002).

The rate at which residues decompose depends on their nature and composition. Under Mediterranean edaphoclimatic conditions, the most restrictive factor is the low availability of water in the summer, which greatly limits the decomposition of residues incorporated into the soil at this time of year (Ordóñez *et al*., 2007).

This work aims to evaluate the fixation potential of C for the different residue types of plant covers located in the lanes of an olive grove, as well as estimating the decomposition dynamics of plant residues after mowing the species and how their development over time affects the surface cover, the residue biomass and the latter's capacity to be a source of C in the soil.

Material and methods

Experiment sites

Experiments were conducted over a period of three agricultural years (2007/08, 2008/09 and 2009/10) at Arenillas olive orchard farm, which was established in 2001 in Fernán Núñez, Córdoba, Spain (37° 40' 1.53" N and 4° 47' W; 266 m above mean sea level) on soil with an 11% average slope. The physicochemical characteristics of the soil are shown in Table 1.

Experimental design

The "Picual" variety trees were planted 5 years before at a distance of 4 m × 8 m. The single plot measured 192 m^2 and it consisted of two central olive trees with a cover crop strip of 12 m × 4 m to each side. The experimental design was randomised complete blocks sited perpendicular to the slope, with four replications.

Cover crops and sowing rate

The cover crops evaluated were: two cruciferous species, common mustard (*Sinapis alba* L. subsp. *mairei* (H. Lindb. Fil.) Maire) and rocket (*Eruca vesicaria* (L.) Cav.), a commercial grass cover called "Vegeta" (*Brachypodium distachyon*) and a spontaneous cover consisting of typical weed flora of the area.

The sowing dates depended on weather conditions: 22nd October 2007, 25th November, 2008 and 30th November 2009. Common mustard and rocket seeds were previously collected from spontaneous wild populations and replicated in the Andalusia Research Center, IFAPA Alameda del Obispo (Córdoba, Spain). Cruciferous seeds were sown and buried 0.5 cm deep following the procedures established in previous field studies (Alcántara *et al*., 2009) at rates of 10 and 3 kg ha^{-1} for common mustard and rocket, respectively, three years. *Brachypodium* was only sown the first year at a rate of 100 kg ha^{-1} following commercial recommendations. The second and third years, *Brachypodium* was established from a cover crop strip which had been left alive the first year and left to sow itself the following seasons.

Sampling

The cover in the experimental olive grove plot was mown in April, and from that date onwards and up to the autumn sowing of the new covers, plant residues were periodically sampled during the agricultural years 2008, 2009 and 2010. In each species, in each block, areas with a high accumulation of residue were selected, and three residue collection points established, which made a total of 12 samples per type of cover and sampling day.

In the three growing seasons, the soil was sampled at the beginning and end of the decomposition period of the plant cover at depths of 0-5, 5-10 and 10-20 cm from each plot. The same occurred in the case of the plant remains, three sampling points being considered in each of the four control subplots per species. The samples were extracted with a Veihmeyer tube and transported to the laboratory in a plastic bag. Subsequently, the soils were air dried and run through a 2 mm sieve.

Analysis of samples

The biomass of the stubble residue was estimated in a 0.25 m^2 metal frame which served to mark out the sampling area and was placed at all the selected points. The residue collected was sent to the laboratory where it was washed with distilled water to prevent contamination in subsequent analysis and was placed in an oven

Table 1. Characteristics of the olive grove soil on which the experiment was conducted

Depth (cm)	OM[1] (%)	N (%)	CEC[2] ($mol_c kg^{-1}$)	Texture (%)			CO_3^{-2} (%)	pH
				Sand	Silt	Clay		
0-10	0.85	0.04	0.24	6.03	43.50	50.48	29.88	8.14
10-20	0.72	0.03	0.22	9.78	39.35	51.13	28.50	8.23
20-40	0.65	0.02	0.23	8.38	41.73	49.90	31.75	8.28
40-60	0.58	0.02	0.22	8.80	41.83	49.37	33.06	8.36

[1] OM = organic matter. [2] CEC = cation exchange capacity.

at 65 °C until it reached a constant weight and it was possible to estimate the amount of dry matter.

The cover percentage was measured following the evaluation per sectors method described by Agrela *et al.* (2003), which is characterized by the use of a 1 m^2 frame divided into 100 reticules. The method consists of a subjective assessment of the different percentages of cover estimated in each reticule on a scale of 0 to 5 according to the greater or lesser amount of cover. Total C in the residue samples was analysed in a LECO elemental analyser.

The soil samples were air-dried, ground and sieved through a 2 mm mesh sieve for subsequent analysis. The determination of soil organic C is based on the Walkley-Black chromic acid wet oxidation method. Oxidisable matter in the soil is oxidised by 1 N $K_2Cr_2O_7$ solution. The reaction is assisted by the heat generated when two volumes of H_2SO_4 are mixed with one volume of the dichromate. The remaining dichromate is titrated with ferrous sulphate. The titre is inversely related to the amount of C present in the soil sample (Sparks *et al.,* 1996).

Cover-residue biomass relation

In order to determine the relationship between biomass and cover percentage, a grade 2 polynomial was used, of the type:

$$Cover_t(\%) = a + (b \quad M_t) + (c \quad M_t^2) \qquad [1]$$

the same as that used by Lyon (1998) in dryland crops, where M_t (kg ha^{-1}) is the residue biomass at instant t. Likewise, the exponential model proposed by Gregory (1982) was used:

$$Cover_t = Cover_{\max}\left[1 - \exp\left(-k \ M_t\right)\right] \qquad [2]$$

where $Cover_t$ is the fraction of cover at the instant t (%), $Cover_{max}$ is the fraction of maximum cover (100% in all cases), k is the coefficient of cover calculated by the model (ha kg^{-1}) and M_t is the residue biomass at the instant t (kg ha^{-1}).

Spatial-temporal distribution of stubble residue in the soil

This section evaluates the variability of that percentage under field conditions. For this purpose, 52 field strips were selected, from which samples of 0.25 m^2 were selected over time.

In order to analyse the temporal stability of the cover percentage in the different strips, a method similar to that proposed by Vachaud *et al.* (1985) was used. This was based on the concept of temporal stability, calculating averages and variance over time.

In this case, unlike the method proposed by the cited authors, we calculated the temporal means of each strip, rather than the relative differences, as this was of interest in order to ascertain the average cover.

$$AC\_strip_i = \sum_{t=1}^{n} \frac{Cover(\%)_{it}}{n} \qquad [3]$$

where $AC\ strip_i$ represents the mean temporal cover in the strip i; n = samplings done in each treatment of residues; $i=1,2...,52$; $Cover\ (\%)_{it}$: cover percentage obtained in the strip i, instant t.

$$\sigma(AC\_strip_i) = \left[\frac{\sum_{t=1}^{n}(Cover(\%)_{it} - AC\_strip_i)^2}{n-1}\right]^{1/2} \qquad [4]$$

with $\sigma(AC\_strip_i)$ denoting the standard deviation of the mean, calculated as an estimator of temporal stability. From this point of view, time-stable locations (strips) are defined as those with a low value of $\sigma(AC\_strip_i)$.

Data analysis

The climatology of the area was monitored in the three years studied, with precipitation and maximum and minimum daily temperature data being evaluated.

The percentage of original dry weight and organic carbon (OC) remaining at each sampling were regressed over time using the linear regression model procedure of SPSS 11.

An analysis of variance (ANOVA) was performed for all the parameters measured and comparison of means was carried out by the Tukey-test with $p \leq 0.05$.

Results

Dynamics of residue biomass

Fig. 1 depicts the temporal evolution of weather and biomass of the plant residues of the different species of cover crop used in the assay for the three agricultural years.

After mowing in the first year, the species with the largest residue mass was *Brachypodium* with 7,323 kg ha^{-1}, followed by *Sinapis* with 3,141 kg ha^{-1}, then *Eruca* with 2,960 kg ha^{-1}, and the least residue mass was found in spontaneous weeds which, at the beginning of the sampling, recorded 2,148 kg ha^{-1}. Throughout the decomposition period, significant differences were noted between the weight of the *Brachypodium* remains and that of the other covers (Table 2). These differences decreased as the plant remains grew.

In the second year, after mowing, the data recorded were as follows: 11,038 kg ha^{-1} for *Brachypodium*, 7,461 kg ha^{-1} for *Eruca,* 6,732 kg ha^{-1} for spontaneous weeds and 5,850 kg ha^{-1} for *Sinapis* (Fig. 1). It can be seen that there was a higher production of residue in the second year in all cases as a consequence both of the seeding of the different species and of the rainfall recorded in the autumn and winter months, which favoured the growth of the cover. In this case, the significant differences in the weight of the residue of the different species are not so clear and vary from one sampling date to another (Table 2).

The exceptional weather conditions during autumn (September-December) 2010, with 550 mm of rainfall in the experimental area, which is equivalent to a normal annual average, allowed plants to emerge and grow normally, thereby restricting the production of residues to a great extent in the third agricultural year. This situation caused a decrease in biomass values after the clearing of all covers, spontaneous weeds registering the best data with 5,949 kg ha^{-1} and *Brachypodium* the lowest figures with 4,137 kg ha^{-1}. No significant differences are appreciated from one species to another (Table 2).

The greatest biomass losses were noted between the months of April and May and from September to October, when rainfall and mild temperatures favoured the activity of microorganisms which decomposed the organic remains.

Dynamics of residue cover

Fig. 2 represents the temporal evolution of the percentage of soil cover for the residues of the different species considered. *Brachypodium* cover registers the

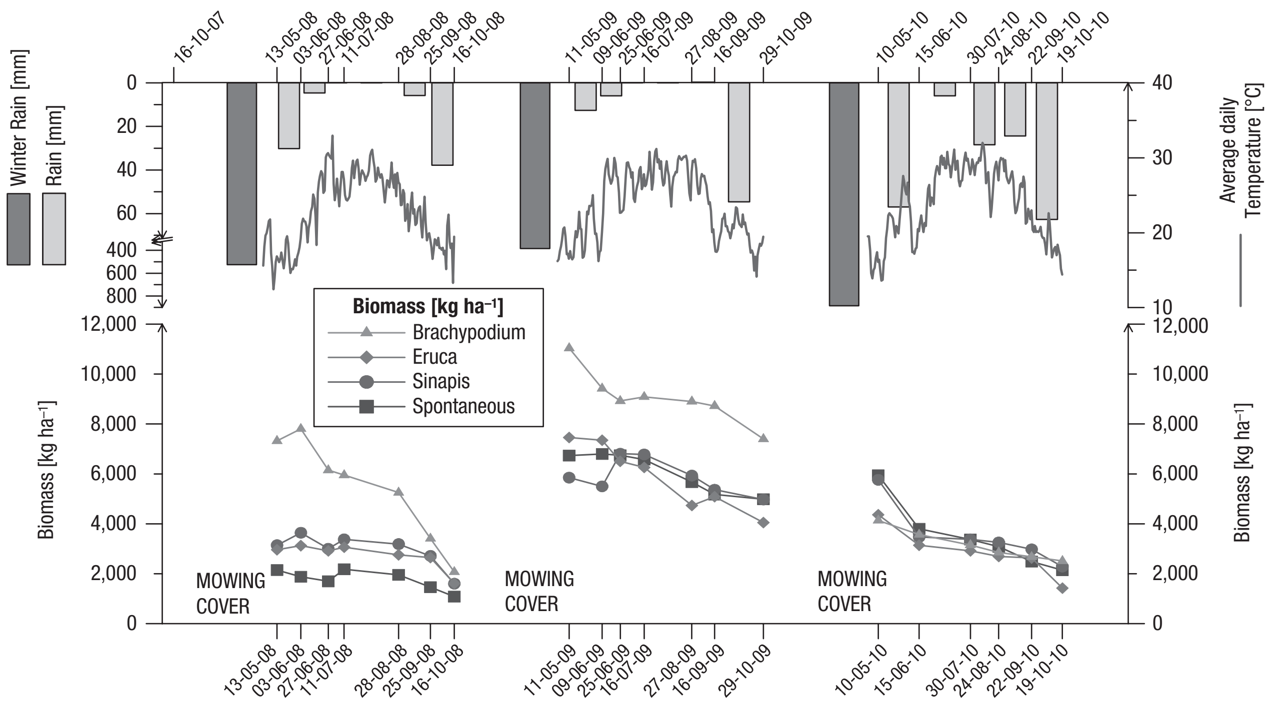

Figure 1. Temporal evolution of the climatology and of the residue biomass mean values of the different species and years considered in the study.

Table 2. Comparisons of residue biomass (RB) dry weight means and of cover means between species for the different years and dates sampled, based on the analyses of variance and the Tukey test. Different letters between covers represent significant differences at a probability level of $p \leq 0.05$

Year	*Brachypodium*		*Eruca*		*Sinapis*		Spontaneous	
	RB	Cover	RB	Cover	RB	Cover	RB	Cover
2008								
13/05	a	a	b	ab	b	a	b	b
03/06	a	a	b	b	b	b	b	b
27/06	a	a	b	b	b	b	b	b
11/07	a	a	b	b	b	b	b	b
28/08	a	a	ab	b	ab	b	b	b
25/09	a	a	ab	b	ab	b	b	b
16/10	a	a	a	b	a	b	a	b
2009								
11/05	a	a	b	a	b	a	b	a
09/06	a	a	ab	a	b	a	b	a
25/06	a	a	a	a	a	a	a	a
16/07	a	a	a	a	a	a	a	a
27/08	a	a	a	a	a	a	a	a
16/09	a	a	b	b	b	c	b	c
29/10	a	a	b	b	ab	b	ab	b
2010								
10/05	a	a	a	a	a	a	a	a
15/06	a	a	a	a	a	a	a	a
30/07	a	a	a	a	a	a	a	a
27/08	a	a	a	a	a	a	a	a
22/09	a	a	a	a	a	a	a	a
19/10	a	a	a	a	a	a	a	a

highest percentage of cover with respect to the rest, with significant differences on all the sampling dates (Table 2). While the trend is usually downward over the summer, in this species the degree of soil cover is maintained at above 80%, protecting the soil when the autumn rains begin and the erosion risk is higher.

In the second year, the trend was similar among the different covers and significant differences were only noticed between *Brachypodium* and the remaining species on the last two sampling dates. In third sample season, *Brachypodium* once again recorded the highest cover values throughout the decomposition period, but no significant differences were observed in regard to the rest of covers (Table 2).

Cover-residue mass relation

Table 3 and Fig. 3 show the result of applying the two models to the relationship between the percentage of soil cover in terms of biomass. The relationship between the soil cover percentage and its biomass was not significant between the variables considered for *Brachypodium*. The high percentage of cover maintained by this species during the whole decomposition period, even with low values of biomass, due to its capacity to regrow, may be the reason for it not fitting the models proposed. Spontaneous weeds provide the best fit to both models, whereas the rest of the species show lower coefficients of determination (R^2), especially *Sinapis*.

In accordance with the experiment data obtained, we calculated the amount of residue necessary to obtain a 30% cover, this being the limit used in the definition of conservation agriculture. The results are presented in Fig. 3 and Table 4. The exponential model (Gregory) shows that we need around 1,000 kg ha^{-1} for all the species, which is larger than quadratic model, although considering a range of cover of 25-35% and 28-32%, measured values were larger than both models (Table 4). The residue mass was piled up covering a portion of soil without being effectively dispersed, and we ob-

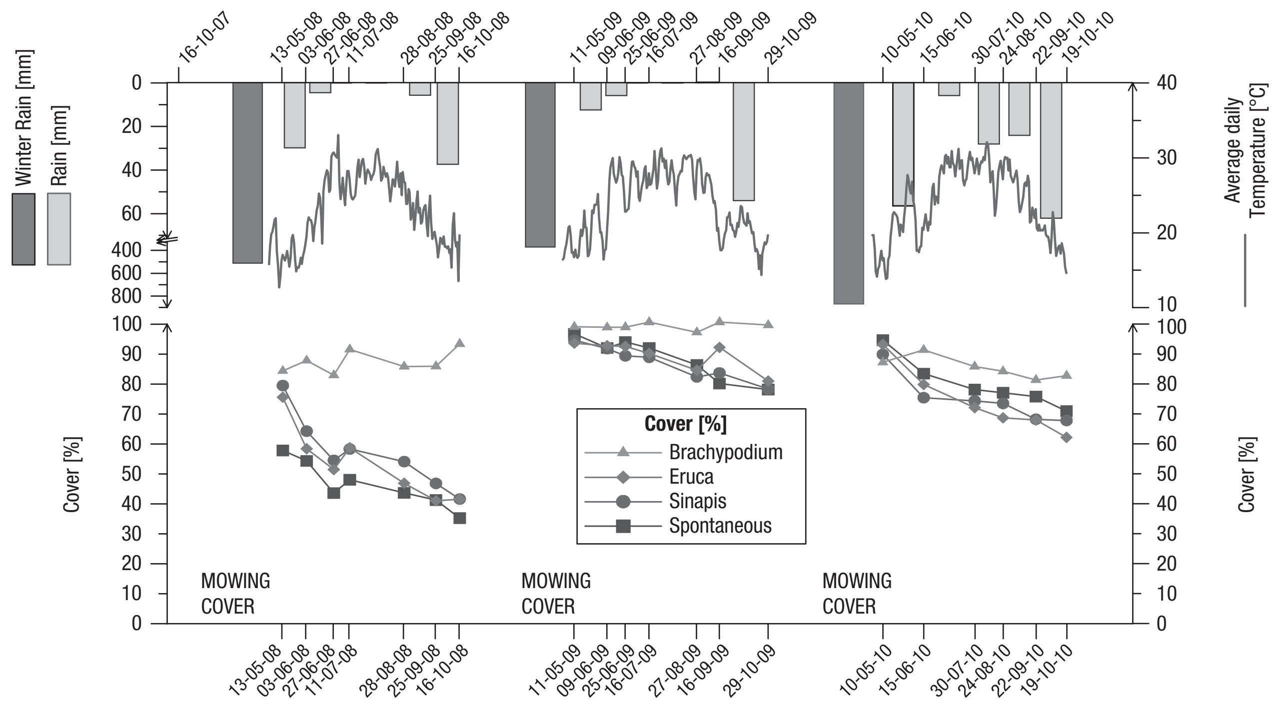

Figure 2. Temporal evolution of the cover percentage for the different species and years considered in the study.

tained amounts of residue mass larger in *Eruca* and *Sinapis* than spontaneous weeds.

Spatial-temporal distribution of the residue on the soil

Fig. 4 shows the average cover of the 52 strips controlled for the different species and seasons sampled. Covers were highly variable in the 2008 season, recording covers of less than 30% and others of 100%. More specifically, cover ranged from minimums of 29, 26, 21 and 12% to maximums of 100, 89, 94 and 68% for *Brachypodium, Eruca, Sinapis* and spontaneous weeds. During the same year, the time stability of the cover did not follow a specific pattern and variations in the standard deviation at control points are similar for the different covers.

In 2009, the favourable growth of the covers resulted in less spatial variability in the percentage of residue cover at the selected points in each of the species. The lowest variation was observed in *Brachypodium* (90%-100% of cover), while the highest variation was recorded by *Sinapis* (41%-100%).

Spatial variability rose again in 2010, with minimum cover values of 48%, 48%, 20% and 47% for *Brachypodium, Eruca, Sinapis* and spontaneous weeds respectively and maximum values of 100% in all covers. The variation in cover followed a similar temporal pattern in

Table 3. Relationship between soil cover and residue mass per unit area for the different covers

Species	Model	Equation	R^2	*n*
Eruca	Quadratic	$Cover_t = 19.184 + 0.0168\ M_t - 9.116 \cdot 10^{-7}\ M_t^2$	0.59	155
	Gregory	$Cover_t = 100\ [1 - \exp(-0.000332\ M_t)]$	0.58	155
Sinapis	Quadratic	$Cover_t = 23.615 + 0.0151\ M_t - 8.462 \cdot 10^{-7}\ M_t^2$	0.50	144
	Gregory	$Cover_t = 100\ [1 - \exp(-0.000323\ M_t)]$	0.49	144
Spontaneous	Quadratic	$Cover_t = 15.782 + 0.0200\ M_t - 1.271 \cdot 10^{-6}\ M_t^2$	0.75	145
	Gregory	$Cover_t = 100\ [1 - \exp(-0.000363\ M_t)]$	0.74	145

R^2 = coefficient of determination. *n* = number of samples.

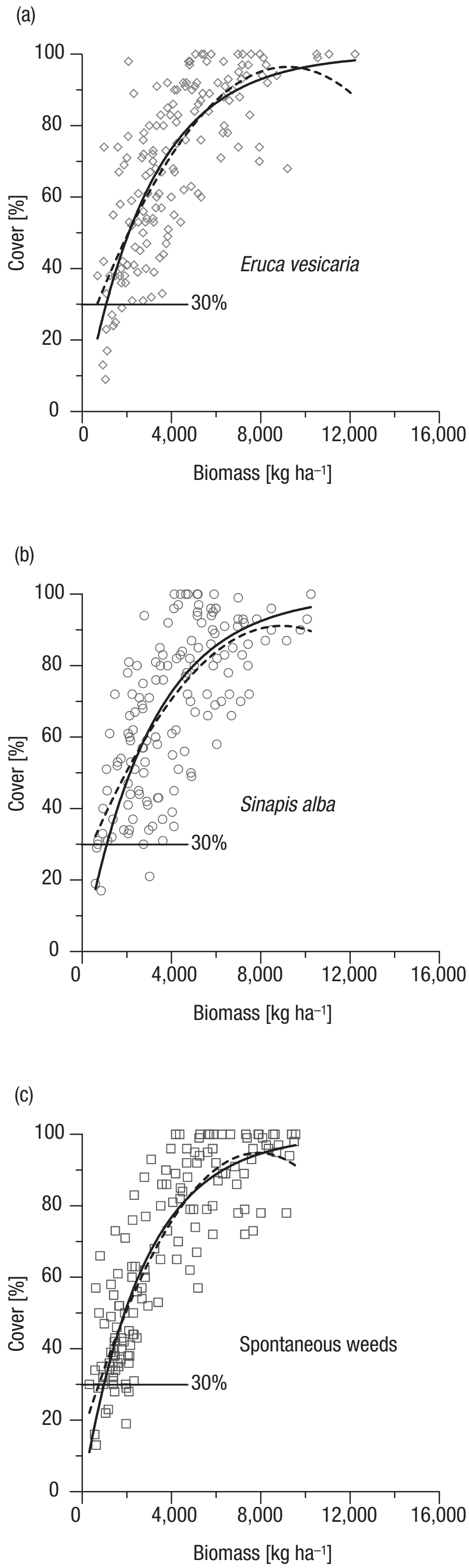

Figure 3. Relationship between biomass and cover of (a) *Eruca vesicaria*, (b) *Sinapis alba* and (c) spontaneous weeds. The fits are quadratic model (---) and Gregory model (—).

Table 4. Residue biomass (kg ha^{-1}) necessary for reaching 30% of cover according to the different species and models considered in the study, and measured values (kg ha^{-1}) for a range of measured cover between 25-35% and 28-32%

Species	Model		Range	
	Quadratic	Gregory	25-35%	28-32%
Eruca	668.02	1,074.32	2,167.60	2,461.00
Sinapis	433.37	1,104.26	2,006.29	1,554.97
Spontaneous	746.29	982.58	1,348.72	1,405.33

both seasons. The highest standard deviations were observed at the points where the percentage of cover was lowest, while greater stability over time was observed at the points where the percentage of cover exceded 85%.

Release of carbon

Table 5 shows the amount of C released and the reduction in the mass of the different species considered in the study after the decomposition period. *Brachypodium* recorded the greatest biomass losses in the first and second years, which gives an idea of the ease of decomposition of the residues of this cover which, at the beginning of the decomposition cycle, had a C/N ratio close to 20, which was lower than that for the rest of the species (*Sinapis*: 34; *Eruca*: 29; spontaneous weeds: 23).

Due to the weather conditions, which affected the growth of the covers and the amount of residues after they were cleared up, spontaneous weeds registered the largest biomass loss in the third year and the highest values of residue mass at the beginning of the decomposition period. As regards the amount of organic C released during decomposition, these values are highly disparate among the different species (Table 5).

Soil carbon fixation

The effect of the decomposition of the residues of the different covers on the concentration of organic C in the soil has been evaluated. Table 6 shows the values of this parameter in the soil for the samplings carried out and the increase in C estimated in the three years during the decomposition period.

The non alteration of the soil, leaving the cover residues on the surface for three consecutive years, has

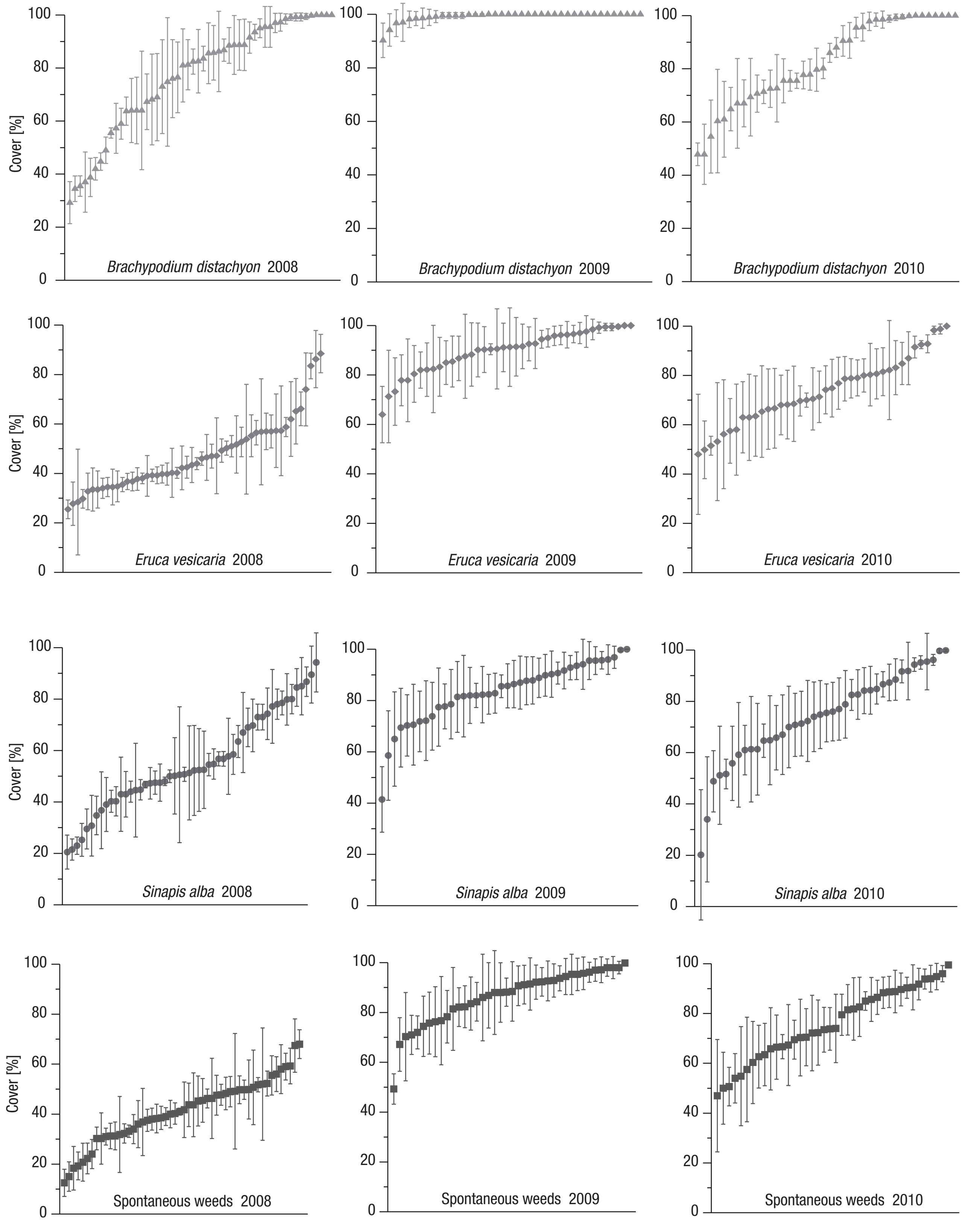

Figure 4. Average cover by ranges in the sample strips. Vertical lines represent the standard deviation obtained in each strip.

Table 5. Loss of residue biomass and release of carbon from plant cover in the experiment plots for the 2008 (157 days of decomposition), 2009 (172 days of decomposition) and 2010 (163 days of decomposition) agricultural years

Year	Biomass (kg ha^{-1})	Organic C (kg ha^{-1})
2008		
Brachypodium	5,253	2,157
Eruca	1,350	588
Sinapis	1,540	666
Spontaneous	1,063	462
2009		
Brachypodium	3,640	1,911
Eruca	3,412	1,471
Sinapis	878	404
Spontaneous	1,745	509
2010		
Brachypodium	1,630	614
Eruca	2,937	1,145
Sinapis	3,477	1,372
Spontaneous	3,809	1,493

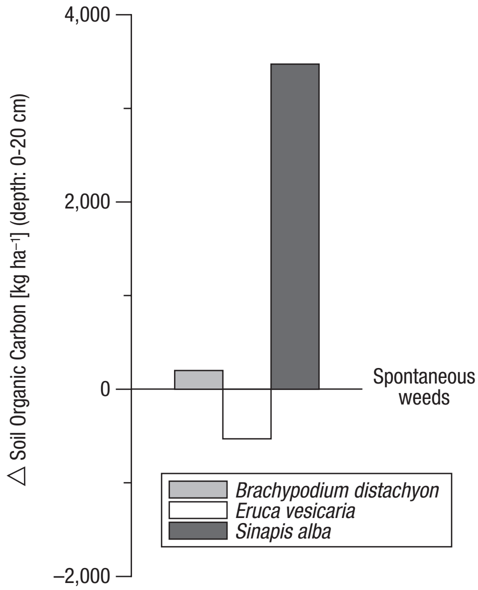

Figure 5. Comparison of the quantity of C fixed by different species of plant cover to that fixed by spontaneous weeds in the entire profile of soil (depth: 0-20 cm).

increased the C content in the different layers of soil considered. Sinapsis fixed the largest amount of C in the entire profile of the soil, although no significant differences in the values of fixed C are observed between the surface and at depth among species.

Most olive growers use spontaneous weeds as soil cover. As a result, the increase or decrease in the amount of C that has been fixed by the different species has been represented in Fig. 5 in relation to that estimated for spontaneous weeds. The planting of cover has fixed 47% and 5% more C in 20 cm of soil than the measure recorded in soils where the native weed flora was left.

Discussion

The decomposition process of the harvest residues are influenced by edaphic and environmental factors like: temperature, moisture, availability of nutrients, microflora and soil fauna, by factors inherent to the residue such as their C/N ratio, content of lignin and soluble carbohydrates, and by management factors like the amount of stubble and its size (Thorburn *et al*., 2001). However, the most important ones are the climate variables and how susceptible residues are to being colonized by microorganisms (Soon & Arshad, 2002). Authors like Ernst *et al*. (2002) have carried out studies on different residues and concluded that the C/N ratio determines its decomposition rate. Ruffo & Bollero (2003) indicated the need for a better knowledge of residue decomposition through research conducted under more realistic field conditions.

In regard to the dynamics of residue cover, the benefits of conservation agriculture systems with regard to soil protection from erosion and an improvement in soil water balance are associated with the presence of plant residues covering the soil at times when there is no crop. However, the percentage of the cover and its persistence depends on the type of residue and on the climate in the area (Gajri *et al*., 2002).

In our case, considering all decomposition period, none of the species recorded mean cover values of below 30% that is the limit over which the soil would be protected from erosion agents (Conservation Tillage Information Center, 1990). Snelder & Bryan (1995) investigated the relationship between cover density and soil loss under simulated rainstorms. In their experiment, a critical threshold occurred with a 55% cover, below which erosion rates increased rapidly.

Analysing the stability of the percentage of cover over time makes it possible to define the persistence of a behaviour pattern in each strip in regard to the rest of strips over time and identify areas with little or excessive cover. The accumulation of biomass or cover in certain areas of the terrain could make later operations performed in olive groves more difficult and affect the

Table 6. Content of organic carbon in the soil (SOC) at the beginning of the 2008 sample year and at the end of the decomposition period of the residues in the third sample year, and the carbon fixed for the three agricultural years considered in the study. Different letters between covers represent significant differences at a probability level of $p \leq 0.05$

Depth (cm)	SOC (kg ha^{-1})		Fixed OC (kg ha^{-1})
	2008	2010	
Brachypodium			
0-5	3,511	5,732	2,221 a
5-10	3,280	3,816	536 b
10-20	5,582	7,104	1,522 a
Eruca			
0-5	4,154	5,707	1,553 a
5-10	3,280	3,968	688 ab
10-20	5,582	6,861	1,279 a
Sinapis			
0-5	4,236	6,592	2,356 a
5-10	3,280	5,099	1,819 a
10-20	5,582	9,097	3,515 a
Spontaneous weeds			
0-5	3,940	5,510	1,571 a
5-10	3,280	4,103	823 ab
10-20	5,582	7,260	1,678 a

decomposition of the residue, as well as areas with little cover reducing the level of protection against erosion (Ayed & Mohammad, 2010).

The study undertaken reveals that the greatest spatial variability of the cover was observed in the first and third seasons when less residue was produced and irregular distribution left areas with a cover of less than 30%.

Regardless of the sample season considered, *Brachypodium* records the lowest standard deviations, which indicates the cover provided by this species is more stable over time.

While most crop residue studies related to erosion control or the effect of tillage on residue retention express residue data primarily as a percentage of soil cover, studies dealing with residue decomposition usually calculate residue losses in terms of mass. Due to the time and work involved in obtaining residue mass data and the difficulty attributed to residue cover determination methods, there is an interest in establishing relationships between residue mass and soil cover for prediction purposes.

As we show in Table 3, the cover coefficients k of the different species are lower than those estimated by Steiner *et al*. (2000) in crops of barley, oat, spring wheat and winter wheat in field experiments, k between 0.0099 and 0.00162 ha kg^{-1}, and also lower than that indicated by Ordóñez *et al*. (2007) for peas (k = 0.0011 ha kg^{-1}). This could be due to the fact that the amount of biomass necessary to achieve 100% cover in the different species of plant cover is much greater than that necessary for the crops previously cited.

López *et al.* (2005) indicated that in order to achieve a 100% cover with barley residue, between 2,000 and 3,000 kg ha^{-1} of biomass are necessary, which contrasts with our data in which 7,500, 5,900 and 6,700 kg ha^{-1} of residues of *Eruca, Sinapsis* and spontaneous grass weeds, respectively, are required to achieve maximum cover. In fact, the values of the coefficient k are very similar to that reported by Gregory (1982) in corn crops, with k = 0.0004 ha kg^{-1}, with residue values of over 8,000 kg ha^{-1}.

In addition to protecting the soil, another important characteristic of the residues is that they supply C. However, this depends on the composition of the residue and on how easily it decomposes. The C release rate of the different residues was estimated, understanding this to be the difference between the content of this element in the stubble when the covers are mown and that estimated in the residue samples collected on different dates.

According to the results shown in Table 5 and considering three years, the C release rate of *Brachypodium* residue was 1.5, 1.9 and 1.9 times higher than that of *Eruca*, *Sinapis* and spontaneous weeds respectively. At the end of its decomposition cycle, *Brachypodium* stubble had lost 72%, 42% and 40% of its initial C content.

The edaphoclimatic conditions of the area and the characteristics of the residue played an important role in the evolution of plant residues. In all cases, the highest percentage of C released by the decomposition of the residues was recorded in the first year because of lower rainfall recorded in the second year. Some authors like Aulak *et al.* (1991) and Baggs *et al.* (2000), mention that moisture is important as a trigger of the the decomposition process and even more so in the case of residues with a low C/N ratio. Authors like Ernst *et al*. (2002) have carried out studies on different residues and concluded that the C/N ratio determines its decomposition rate

The relationship between the amount of biomass and C released by the decomposition of residues approaches 2.5, regardless of the type of cover and sample season considered. This indicates that 1 kg of C is released for every 2.5 kg of biomass that are lost.

It has been amply proven that when changing from traditional agriculture (intensive tillage) to conservation agriculture, the content in OM in the soil increases over time, with all the positive results that this brings with it (Bravo *et al*., 2007).

The C sequestration values observed in Table 6 were higher than those estimated by Castro *et al*. (2008) in olive grove soil where plant cover was maintained for 28 years, and similar to those estimated by Márquez *et al*. (2008) in an olive grove with a cover for 4 years. In both cases, the cover was spontaneous weeds.

González *et al.* (2012) in a study with a statistical analysis of cover crops reviewed studies show that those with native species obtained a sequestration mean of 1.78 Mg ha^{-1} yr^{-1}, while those with sowed species reached 1.16 Mg ha^{-1} yr^{-1}. In our case, *Sinapis* and *Brachypodium* sequestered 3,618 and 207 kg ha^{-1} more than spontaneous weeds. Considering three years and a soil depth of 20 cm, the behaviour sequence of the different species in favouring the fixation of organic C in the soil was *Sinapis* > *Brachypodium* > spontaneous weeds > *Eruca.*

As final conclusions, under the edaphoclimatic conditions in southern Spain, the plant residues remaining from the olive grove covers when the latter are mowed in April have the two-fold task of protecting the soil from intense spring and summer rain and favouring the maintenance of soil fertility with the release of C and nutrients as they become degraded. The summer protection of the soil by the residues of different species has been assured as, in the worst of the cases (*Sinapis*), 38% of the cover was lost until the next cover is established. Despite that, a spatial variability study indicates the convenience of uniform residue distribution in order to ensure cover in the entire area and avoid points that lack protection and could restrict the benefits of cover when faced with erosion.

Likewise, the mass-to-cover relationship established in this study for different cover residues could be used to estimate soil cover from residue mass throughout the decomposition period by using a single *k* coefficient for each species.

As regards the protection of the soil, *Brachypodium* developed the greatest amount of biomass and maintained the highest and most stable levels of cover throughout the period under analysis.

In reference to the effect of plant covers on C sequestering, *Sinapis* fixed the most C, namely 7.7 Mg ha^{-1} in three years, which represents 44%, 47% and 54% more than the amount fixed by *Brachypodium*, spontaneous weeds and *Eruca,* respectively.

Although spontaneous weeds are the most popular alternative among farmers when it comes covering the soil of their olive groves, the results of this study reveal that other types of plant covers not only improved soil fertility, but also yield more environmental benefits as regards their contribution towards reducing erosion processes and fighting climate change.

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