Tesis Doctoral

Cover crops management as conservation system and improvement of soil quality and runoff water in the Andalusian olive grove

Manejo de cubiertas vegetales como sistema de conservación y mejora de la calidad del suelo y de las aguas de escorrentía en el olivar andaluz

MIGUEL ÁNGEL REPULLO RUIBÉRRIZ DE TORRES

CÓRDOBA 2014

TITULO: *Manejo de cubiertas vegetales como sistema de conservación y mejora de la calidad del suelo y de las aguas de escorrentía en el olivar andaluz. Cover crops management as conservation system and improvement of soil quality and runoff water in the andalusian olive grove*

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14071 Córdoba

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CONSEJERÍA DE AGRICULTURA, PESCA Y DESARROLLO RURAL

IFAPA
Área de Producción Ecológica y Recursos Naturales
Centro Alameda del Obispo, Córdoba

Universidad de Córdoba
Departamento de Agronomía
E.T.S. de Ingenieros Agrónomos y Montes

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LÍNEA DE INVESTIGACIÓN: Análisis de Procesos Hidrológicos e Hidráulicos y sus Implicaciones Ambientales

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Córdoba 2014

TÍTULO DE LA TESIS:

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INFORME RAZONADO DEL/DE LOS DIRECTOR/ES DE LA TESIS

(se hará mención a la evolución y desarrollo de la tesis, así como a trabajos y publicaciones derivados de la misma).

Los directores de la tesis: Dr. Rafaela Ordóñez Fernández y Dr. Rosa M. Carbonell Bojollo, informan que el doctorando ha desarrollado los objetivos previstos compartiendo su formación con la investigación. El doctorando ha realizado estancias en el instituto italiano IMAMOTER (CNR) de Turín, Italia (mayo-julio 2013); y en el departamento de Química y Análisis agrícola de la Universidad Politécnica de Madrid (abril-mayo 2014). La tesis se presenta en capítulos, tres de los cuales se corresponden con tres publicaciones aceptadas en revistas indexadas.

Por todo ello, se autoriza la presentación de la tesis doctoral.

Córdoba, _29_ de _octubre_ de _2014_

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Esta Tesis Doctoral ha sido realizada gracias a la beca predoctoral (modalidad 3) nº 19 del programa de formación del personal técnico e investigador del IFAPA. Resolución de 2 de noviembre de 2010 (BOJA 220, 11/11/2010).

Los trabajos incluidos en este trabajo de investigación han sido subvencionados por el Instituto Andaluz IFAPA (Consejería de Agricultura, Pesca y Desarrollo Rural de la Junta de Andalucía) y financiados por el Programa Operativo del Fondo Social Europeo 2007-2013 de Andalucía, en el ámbito de actuación prioritario del Eje 3 (Aumento y mejora del capital humano), en un 80%.

AGRADECIMIENTOS

Son muchas las personas y entidades a las debo gradecer este trabajo y mi formación como doctor. Me disculpo de antemano porque seguramente me dejaré alguna atrás.

En primer lugar tengo que empezar por mis directoras de tesis: Fali y Rosa, mi madre y mi hermana mayor en esto de la investigación, pero que prácticamente lo son también fuera de este ámbito. Especialmente a ti Fali que siempre apostaste por mí a pesar de la paciencia que sabes que hay que tener conmigo.

Al resto de mi familia ifapeña, el personal del laboratorio de suelos y riegos: Carmen, Caty, Eli, Ana y Pedro, que ha sido un director más para mí. Si Fali es la madre, Pedro el padre. Además en muchas cosas he salido más al padre… Este es un trabajo de equipo y sabéis que nada de esto habría sido posible sin vuestra dedicación, vuestro ánimo, el buen ambiente que transmitís y vuestro cariño conmigo, siempre seré vuestro niño. Mención especial a D. Manuel Armenteros sus conocimientos y su amistad son impagables. Siempre resuelves cualquier contratiempo que pueda surgir. Es un lujazo trabajar con todos vosotros.

Y a toda la buena gente que está o ha estado un tiempo con nosotros, casi siempre para ayudarme directamente en mis trabajos, en su día estuvo Julio, ahora contamos con Manolo Moreno y hace ya tiempo que tengo la suerte de contar con Javi para todo lo que haga falta. Vuestra ayuda y todos nuestros “enreos” hacen que dé gusto ir a trabajar. Manolo, gracias por tu ayuda con la portada. Y a aquellos que de manera puntual también han estado con nosotros.

A todos los que han colaborado de manera directa en los trabajos publicados y no he nombrado antes: Antonio, Cristina, Javier; siempre resolvéis mis dudas.

A Juan Vicente Giráldez, que más que un tutor y responsable de la línea de investigación ha sido como otro director más.

A los compañeros del despacho presidencial, los que estamos y los que han pasado ¿eh Currito? A los patólogos Antonio, Pepe y Fran, al resto de becarios que formamos tan buen grupo. Dentro de los becarios destacar también a los becarios IFAPA (los Koalas) que tan buenos ratos hemos pasado, compañeros de cursos y de fatigas, la buena conexión entre nosotros nos ha resuelto muchas dudas. Y a todos aquellos que durante todos estos años hemos compartido malos y, sobre todo, buenos momentos por aquí.

A todos los compañeros de AEAC-SV, mis iniciadores. Mucho de lo que sé es debido a todo el tiempo que estuve trabajado con vosotros, bueno, y que seguimos trabajando aún. Gracias a Emilio por tus contactos para la defensa de la tesis.

A todos los compañeros de IMAMOTER de Turín que tan bien me acogieron durante mi estancia allí, especialmente a Marcella y Francesca. Y a Antonio Vallejo y su muy buen equipo de la Universidad Politécnica de Madrid.

A mi familia por su amor y dedicación conmigo, que aun viva con vosotros ha facilitado mi dedicación a mi trabajo y es también signo de lo que os quiero. A mis amigos a quienes no he podido dedicar todo el tiempo que hubiese querido y que se merecen, porque siempre me aportáis luz en lugar de “sombras”. A Araceli, por el tiempo que mi trabajo me ha quitado de estar contigo, y que espero tener a partir de ahora, por todo tu cariño y comprensión.

Finalmente agradezco de todo corazón a Joaquín, mi fiel compañero de batalla, todo el tiempo que hemos pasado juntos. Llegaste, como caído del cielo, justamente para ayudarme en mis trabajos de campo cuando empezaba mi proyecto de fin de carrera. Casi todos los días de campo conté con tu inestimable ayuda tanto en mi proyecto como posteriormente en los trabajos del doctorado, hasta el día de antes de dejarnos inesperadamente y volver de manera repentina a de donde caíste. Tu trabajo abajo en carpintería, tus conocimientos de campo, tu disponibilidad y tu paciencia conmigo han sido fundamentales. Siempre recordaremos tus inventos, tus comentarios, tu puntualidad y hasta tu música.

A aquellos que no he nombrado por descuido o olvido. No sé si están todos los que son pero seguro que son todos los que están.

A todos gracias.

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Chapter I.

Introduction, objetives and structure of the thesis

Chapter I. Introduction, objetives and structure of the thesis

I-1. INTRODUCTION

The olive tree is a species that is very well adapted to the Mediterranean climate; the Mediterranean basin has more than 5 million ha of olive groves, of which 2.58 million ha are located in Spain, and with 60% of that figure concentrated in Andalusia (MAGRAMA, 2013). Over the last 20 years, Spanish production has doubled (European Commission, 2012).

This crop is not particularly demanding in terms of water and nutrients, which has meant that traditionally it has been cultivated in marginal areas of low soil fertility and marked inclines (Semple, 1931). The olive tree can grow in rocky soils or low productivity soils, which makes alternating with another crop in the area difficult, particularly with arable crops. In Spain, about 60% of olive cultivation is carried out in adverse locations (European Commission, 2012).

Tillage has traditionally been the standard method of managing agricultural soils. There are three basic purposes of tillage: preparing a suitable seed bed, soil decompaction and weed control. The advent of tractors resulted in an increase in tillage power and frequency, greater depth of tillage, sometimes with soil turnover, and a significant reduction in labour time.

Tillage would seem to encourage infiltration since it breaks the surface crust, but it causes compaction at the depth beyond the reach of the plough, creating a plough pan. Coupled with the development of new farming tools, this has resulted in excessive tillage leading to particle disintegration, surface crusting which reduces infiltration, and creation of plough pans which increase runoff (Giráldez, 1997).

Furthermore, the Mediterranean climate is characterized by certain features: 70-80% of the total annual rainfall is concentrated in autumn and winter months, and summers are normally very dry and hot. Farmers must therefore attempt to store as much of the water content as possible in their crop soil during the wet months as this generally results in increased production (Pastor *et al.* 2004). To this end, farmers have endeavoured to remove the natural vegetation that competes with the olive for water and also for nutrients. With the primary aim of controlling weeds, tillage has intensified, accelerating the loss of soil and organic matter (Pulleman *et al.,* 2005), which makes the soil more easily erodible (Reicosky *et al.,* 1997).

According to experts, the principal environmental problem in Andalusian olive groves is soil erosion and degradation, chiefly in areas with steep slopes, but also in areas with moderate slopes. Data from the National Action Programme to Combat Desertification indicate that extensive areas of Andalusian olive cultivation far exceed soil loss rates of 25 tonnes per hectare per year, more than 25 times over the natural rates of soil formation. As such, this situation is environmentally unsustainable.

A number of studies point to significant soil losses in woody crops. Laguna and Giraldez (1990), for example, estimated annual losses in olive groves of between 60 and 105 Mg ha^{-1} $year^{-1}$. Subsequent studies give somewhat lower values: 41 (Raglione *et al*., 1999), 41.4 (Bruggeman *et al*., 2005), 21.5 (Gómez y Giráldez, 2007) and 19 Mg ha^{-1} $year^{-1}$ (Gómez *et al.* 2009b) in plots under conventional tillage. These erosion ratios are well above what is considered acceptable (Montgomery, 2007). Soil loss is such that erosion is considered the biggest environmental problem facing olive cultivation (Beaufoy, 2002).

The factors which have the greatest influence on soil loss are the intensity of rainfall events and the slope gradient and length (Martínez-Raya *et al.,* 1993), as the greater it is, the greater the runoff and transport of particles. In Andalusia, a fifth of all olive groves are situated on slopes with a gradient of over 20% (Araujo, 2014) and torrential rainfall is becoming ever more common, which makes it one of the most at-risk regions.

The EU has attempted, by means of the Common Agricultural Policy (CAP), to change this unsustainable model of traditional tillage and move towards a sustainable system. Some aspects of soil protection were included in the CAP after the concept of sustainability was introduced in 2003, within the framework of "Good Agricultural and Environmental Conditions" (GAEC). Thus, the new proposal for rural development incorporates objectives for sustainable management of natural resources and the adaptation and mitigation of climate change by promoting soil management approaches which facilitate carbon sequestration in both agriculture and forestry. The "greening" of the first pillar of the CAP 2020, proposed by the European Commission, is expected to improve the situation, particularly in relation to the problem of soil erosion and organic matter (OM) content. But the reality is that most farmers still use traditional tillage systems.

Soil regeneration is slow and at times extremely hard to achieve. Consequently, soil is considered a non-renewable resource and its conservation must accordingly be made a priority. Soil loss leads to a decrease in natural soil fertility due to the loss of OM and nutrients from the system, especially since the upper horizon is usually the most fertile. It also produces a decrease in the biological or productive potential of the soil which, over the medium-to-long term, could lead to the degradation of the area. In addition, the nutrients washed away from the crop are converted to contaminants that may give rise to problems of eutrophication.

A number of current farming techniques that completely bypass the use of tillage are regarded as "Conservation Agriculture" (CA). It is a broad concept characterized by minimal physical alteration of the soil, protecting the soil by means of a permanent cover on the surface, and crop rotation (FAO, 2014). CA combines profitable agricultural production with environmental protection and sustainability. It can be put into practice in a wide range of ecological zones and farming systems, where it forms the basis for a sustainable intensification of production. The CA approach also facilitates the integration of different production sectors, such as crop-livestock integration and the integration of trees and pastures in the agricultural landscape. The principle CA methods are direct seeding in arable crops and the use of cover crops in permanent crops.

In the recent past, before the use of cover crops in olive groves, a no-tillage technique was used as an alternative to conventional tillage. It involves bare soil treated with residual herbicides and no tillage pass at all. This system reduces the cost of weed control but leaves the soil entirely unprotected by vegetation. The first rains cause surface crusting and machinery use causes compaction that is not counteracted by the temporarily mellow soil that tillage produces. As such, infiltration is significantly reduced. Studies such as that of Francia *et al.* (2000) note that although soil loss may be somewhat lower than with conventional tillage, higher runoff losses occur, which means that the applied chemical products are more easily washed away with the resulting pollution that entails. Subsequent studies showed greater soil and water losses in no-tillage with bare soil compared to conventional tillage and cover crop systems (Francia *et al.* 2006; Gómez *et al*., 2009a).

Furthermore, the flow of water and sediment also causes surface runoff of nutrients, which reduces soil fertility. Once outside of agricultural use, these nutrients become pollutants and the runoff provides the means of their dispersal (Smith *et al*., 1993).

To make better use of soil resources, olive trees are placed in planting frames which leaves an unprotected area between trees. In conventional olive groves, the canopy normally provides coverage of less than 35% of the cultivated area (Pastor, 1998). Olive trees and other woody crops are thus considered crops of limited vegetation cover.

The most effective way to protect soil from erosion is to reduce or nullify the force of the rain. This is made possible by establishing a cover that is able to sufficiently dissipate the impact energy of the raindrop on the soil, preventing the disintegration of structural aggregates of surface soil horizons as well as slowing overland flow. When rain strikes the surface, the soil compacts at the point of impact, generating a wave of pressure that is transmitted through the pores resulting in an erosion crust (Bielders *et al.*, 1996).

The existence of a vegetation cover on the ground in the area between olive trees not only dissipates the kinetic energy of raindrops, but also reduces the overland flow, causing water to be retained and allowing it to be incorporated into the soil, thus reducing the risk of runoff and erosion. Gomez and Fereres (2006) found reductions in soil loss of more than 50% with the use of cover crops compared to conventional tillage. Many studies show that planting cover crops reduces water and soil loss (Rodríguez-Lizana *et al*., 2007; Ordóñez *et al*., 2007a), which also helps maintain soil fertility.

The percentage reduction in soil loss generally lies between 50 and 90%, as the results of Francia *et al.* (2006) y Ordóñez *et al.* confirm. There results of Gómez *et al.* (2009a) were similar, showing that use of cover crops led to a 93% reduction in soil loss compared to bare soil. Gómez *et al.* (2011) carried out a comparison of the two soil management systems in vineyards and olive groves in south-western Europe. This study also indicated annual reductions in losses of water, soil and nutrients with the use of cover crops. Espejo-Pérez *et al.* (2013) reduced erosion by an average of 76% in a study carried out in micro-plots in Andalusian olive groves.

Moreover, the development of sustainable agricultural systems requires an understanding of the quality and evolution of the residues generated by farming practices, in order to devise strategies for their management. The decomposition process of plant residues plays a key role in ecosystems as it influences the formation of soil organic matter and the release of nutrients to the plants (Prescott 2005).

In terms of fertility, a cover performs a dual function: on the one hand it reduces the loss of nutrients in soluble or sediment form caused by runoff and erosion; on the other hand it contributes to nutrient absorption during the dormancy period of the olive tree as, after mowing, its decomposition contributes to soil mineralization (Weiner *et al.,* 2002).

In most crops, the quantification of nutrients from the decomposition of residual biomass is often underestimated, with the consequent over-application of inputs which negatively affect the environmental and economic sustainability of the system. Many studies of decomposition have been conducted which examine the relationship between the chemical characteristics of plant residues and the weight lost by the material during decomposition. There are fewer studies evaluating the effect of the interaction between residue quality and decomposition rate on underlying soil fertility (Sariyildiz and Anderson, 2003; Semmartin, 2006).

The decomposition process depends on the edaphic environment, on inherent characteristics of the residue such as its C:N ratio, lignin content and soluble carbohydrates content, as well as on management considerations such as amount, distribution (Khalid *et al.* 2000a; Lim and Zaharah, 2000) and residue size (Khalid *et al.* 2000b).

In general, most papers in the literature focus on the decomposition of arable crop residues left on the soil after the harvest (Douglas and Rickman, 1992; Stiener *et al.,* 1994). Some notable studies in Spain include analyses of no-tillage systems (Quemada y Cabrera, 1997; López *et al*., 2003; Quemada, 2004; López *et al*., 2005), and in regards to Andalusia, the work of Ordóñez *et al.* (2007b) and Rodríguez-Lizana *et al.* (2010) is particularly noteworthy, as there are few studies of covers in woody crops.

Within the context of olive cultivation, Hernández *et al.* (2005), Castro, *et al.* (2008) and Nieto *et al.* (2010) examined the effect of various cover management approaches in terms of improving soil fertility. These and other authors such as Lal (1997), Smith *et al.* (2000) and Gómez *et al.* (2009a) show that changes to the surface of an agricultural soil, such as the use of a vegetation cover, leads to an increase soil organic carbon (SOC) due to both the reduction in OM loss caused by erosion as well as the decomposition of organic residue.

There are few studies on using pruning residues for cover. The high C:N ratio and low moisture content of these residues means that that they are characterized by slow decomposition rates (Ramos, 1999). Ordóñez *et al.* (2001) evaluated the effect of maintaining a continuous cover of olive pruning residues over a period of six years, revealing improvements in the physical and chemical properties of the soil. Rodríguez-Lizana *et al.* (2008) proposed the use of pruning residues as a cover in order to reduce losses of soil, P and K compared to conventional tillage. Nieto *et al.* (2010) used a carbon model to estimate the carbon sequestration potential and increase in SOC due to different treatments with pruning residues.

In the earliest studies of vegetation covers, these covers were situated in the central area between the lines of olive trees. The most common approach was to use the naturally-occurring spontaneous vegetation of the region as cover, reaped either chemically or mechanically. The soil loss in this system was compared with the loss generated in tillage and bare soil systems (Civantos and Torres, 1981). Later, covers were sown between lines of olive trees in order to ensure sufficient cover. Gramineous species such as barley were among the first to be used (Castro, 1993) along with legumes (Humanes and Shepherd, 1995; Saavedra and Pastor, 1996). Pastor *et al.* (2000) compared planted and spontaneous legumes. Saavedra and Shepherd (2002) surveyed studies carried out with different types of cover and management systems.

González-Sánchez *et al.* (2007) identify the following basic types of cover:

- Spontaneous vegetation cover: consists of the natural regional flora. Farmers can let this grow freely, or they can manage it by selecting some species, usually gramineous plants. In order to do so, they have to apply herbicides that eliminate broadleaf species in autumn or early winter. To manage such a cover, a strip should be left to complete its cycle and germinate, thus providing a seed bank to ensure the regrowth of the cover the following season. Spontaneous cover is the one most widely used by farmers as it is the most economical. Sometimes it is the only viable option if the topography of the area prevents sowing. 95% of the olive groves in Spain that use a cover (30% of the total area of olive groves) use a spontaneous vegetation cover (MAGRAMA, 2013).
- Sown cover: recommended in soils with high erosion levels, soils that have previously been managed with tillage, or bare soil that may have lost a lot of its seed bank and would therefore see little spontaneous growth of cover or the growth of hard-to-control species. Although it offers many benefits, sown covers make up only 1% of the surface area of olive groves with a cover (MAGRAMA, 2013).

  - Gramineae: Covers made up of gramineous plants provide a high degree of soil cover and are easy to control. They are not typically particularly tall crops and thus they present little competition to the olive tree. The most widely-used are barley (*Hordeum* ssp), ryegrass (*Lolium* ssp) and brome (*Bromus* spp.) This paper examines a newer species, "Vegeta" (*Brachypodium distachyon*). It is a short plant which nevertheless produces a lot of biomass, and its cycle is shorter than the most common gramineous species, which means less competition with the olive trees.
  - Cruciferae: These species are well known by farmers as they usually form part of the spontaneous flora of olive groves. Their taproot can help reduce compaction (Wolfe, 2000), but they are particularly useful due to their potential for disease control, especially *Verticillium dahliae* (Cabeza-Fernández and Bejarano-Alcázar, 2008), which is currently being studied by plant pathologists. Some species with high glucosinolate content can have a toxic effect on fungal microsclerotia (Mayton *et al.* 1996). Some of the most beneficial species were studied by Alcántara *et al.* (2009; 2011), of which, *Sinapis alba* subsp. *mairei*, *Eruca vesicaria* and *Brassica carinata* particularly stood out.
  - Legumes: From an agricultural point of view, legumes play an important role in terms of their ability to fix atmospheric nitrogen due to their symbiosis with Rhizobium bacteria. When legume residue is left on the surface or incorporated into the soil it provides part of the main crop’s N requirements as it decomposes (Guzman and Alonso, 2001), acting as a green manure. One disadvantage is their low persistence in the soil due to their low C:N ratio, which means faster residue decomposition and can leave the soil unprotected in early autumn. Those most frequently used as covers are clovers (*Trifolium* spp), vetches (*Vicia sativa* and *Vicia villosa*) and bitter vetch (*Vicia ervilia*).
- Dead mulch: Made up of non-living elements, it offers the great advantage of not competing with the main crop for water and nutrients. It may be composed of pruning residues, leaves stripped from olives in the mills, or even stones. The pruning residues have to be shredded in a grinder and applied to the soil. Shredding eliminates the risk of olive bark beetles (*Phloetribus scarabeoides*), even in the case of coarsely-ground residue. Such residues are extremely beneficial as they increase the content of organic matter and nutrients in the soil, form a durable cover and improve soil structure. They also have a marked effect on weeds thus reducing the use of herbicides. The drawback of this type of cover is the potential spread of disease. In order to avoid this, it is advisable to remove all affected material in the olive grove, by pruning and isolating it, so that the infected residues are not spread throughout the plantation. The surface area of olive groves with this type of cover represents 4% of the total area of olive groves with cover in Spain (MAGRAMA, 2013).

The use of moss as a vegetation cover is currently being researched (Saavedra, 2013), especially in cases where it naturally occurs in the olive grove. It would provide a permanent cover that would not compete with the main crop and could possibly reduce the use of herbicides in managing the cover.

Originally, the main objective of covers was to protect against large losses of soil resulting from conventional tillage. However, other benefits were observed, such as improved hydric balance (Márquez et al., 2007) if managed appropriately; weed control (Hatcher and Melander, 2003); and improved soil in terms of soil organic matter and nutrient balance (Bowman and Billbrough, 2002).

Lastly, it should be noted that the implementation of covers has been officially promoted via the CAP, which has been incorporating environmental criteria (Calatrava and Franco, 2011). It was initially based on subsidized voluntary programmes. Council Regulation (EC) 2078/92 included agri-environmental measures. This was later replaced by Council Regulation (EC) 1257/99 and the Ministry of Agriculture, Fisheries and Food published Royal Decree 4/2001, establishing a grant scheme for environmentally-friendly production methods. Subsequent CAP reforms established direct aid to farmers through Council Regulation (EC) 73/2009, implemented in Spain via Royal Decree 486/2009, which set out the statutory management requirements and the appropriate agricultural and environmental conditions that farmers must meet in order to receive direct payments.

Agri-environmental assistance, developed by communities, has increased the implementation of vegetation covers, especially in Andalusian olive groves. Currently 40% of the total surface area of Andalusian olive plantations have some kind of cover, compared to 30% nationally (MAGRAMA, 2013). These figures highlight not only the need for studies, but above all the need for the dissemination and transfer of knowledge in this field to farmers.

Some studies and measures have been implemented via the European Union’s LIFE programme ("The Financial Instrument for the Environment"). Specifically, the LIFE “Sustainable Doñana Project” (LIFE00 ENV / E / 000547) produced very good results in combating soil erosion in the olive groves of the Doñana National Park. Tests were carried out on 33 farms covering 320 ha, chosen on the basis of their high exposure to erosion and their representativeness of the most common types of soils in the area.

It was estimated that LIFE investments would prevent a total of 345 000 tonnes of soil erosion, which translates to about 10 cm of soil in 230 ha of agricultural land, and that this would greatly reduce the pressure of sediments in the Guadiamar river (European Commission, 2010). The implementation of this project has provided a boost to the use of sustainable practices in the region, mainly due to the great efforts made in raising public awareness and informing local farmers about the importance of preserving natural resources and the landscape. The EU recognizes that the problem for conservation agriculture is not so much the cost as the lack of knowledge required on the part of farmers in order to implement such practices (European Parliament, 2014).

I-2. OBJECTIVES

The ultimate aim of this study was to provide technicians and farmers with a range of possible uses of covers according to their needs, presenting information on which species or treatments are best for solving a given problem based on the characteristics of their farming.

In particular, we aim to use a sprinkler rainfall simulator to determine the effect of the coverage and intensity of rainfall on the generation of runoff, soil loss and loss of SOC in the sediment washed away. To this end, comparisons were carried out of species from different families used as a vegetation cover, spontaneous grass and a tillage system (Chap. II).

We also aim to evaluate the decomposition of different types of covers, observing their ability to keep the soil covered (Chapters III and IV); to study their potential to fix atmospheric CO_2 and their use as a source of carbon (Chapters III and IV.); and the release and contribution of macronutrients (Chapter V) to the soil. Live gramineous and cruciferous plants were used (Chapter III) as well as a dead mulch of pruning residues (Chapters IV and V) with different treatments featuring different application volumes and residue size.

I-3. STRUCTURE OF THE THESIS

This thesis is divided into six chapters:
Chapter I: General introduction and objectives.
Chapter II: This chapter outlines the reductions in runoff, erosion and carbon losses according to the different species used as cover compared with a tillage system. This is an article which is being prepared for publication.
Chapter III: Presents a published article about the carbon sequestration potential and soil protection with a live cover of gramineous and cruciferous plants.
Chapter IV: Contains a published article on a study of dead mulch cover made up of pruning residues applied to the soil. The article takes an environmental perspective on soil protection, examining soil fertility and OM content within this context.
Chapter V: Published article featuring data from the same experiment as in Chapter V, developed with dead mulch cover made up of pruning residues. The release of N, P and K from the residue is studied as well as the resulting soil improvement in terms of these macronutrients.
Chapter VI: A summary and general conclusions of the study are detailed.

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Chapter II.

Efficiency of some gramineous, cruciferous and leguminous species as cover crop in olive groves to reduce runoff, erosion and soil organic carbon loss

Chapter II. Efficiency of some gramineous, cruciferous and leguminous species as cover crop in olive groves to reduce runoff, erosion and soil organic carbon loss

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II-Abstract

Olive, one of the main crops of the Mediterranean area, is usually planted following a pattern which leaves a large bare soil area between the trees, enhancing erosion losses. The erosive processes are more intense in steep slopes, where many olive orchards are located. Cover crops represent an effective soil conservation practice for olives cropped in steep slopes. The use of cover crops in tree orchards, either spontaneous or periodically drilled, has increased in recent years as a management system to prevent soil and water losses. In order to compare runoff, erosion and soil organic carbon (SOC) losses in sediment, several trials were carried out in plots located in the south of Spain over a two year period. The plots were rectangles 5 m wide and 10 m long. Several covers were adopted including a gramineous (*Brachypodium distachyon*), a cruciferous (*Sinapis alba*) and two leguminous plants (*Vicia sativa* and *Vicia ervilia*). The covers were compared with conventional tillage and a cover crop of spontaneous weeds, the cover commonly used by most farmers. Rain was simulated with a set of sprinklers which yield constant rates of 15 and 40 mm h^{-1} at two different times of the year: when the cover was in its development phase and after it was mechanically mowed. Runoff hydrographs and sediment concentration were registered and total amount of runoff, sediment yield and SOC losses were determined. The extended root system of crucifers and their fast growth, which favours infiltration, reduced runoff in the *S. alba* plot by over 95% with respect to conventional tillage and spontaneous weeds. All cover crop treatments significantly reduced soil loss rates compared to the tillage system. *S. alba*, *V. ervillia*, *B. distachyon*, spontaneous weeds and *V. sativa* followed in decreasing reduction order with respect to the tillage treatment with reductions grater than 93%. Compared to spontaneous weeds, *Sinapis alba* achieved a 91.1% of reduction in both losses. The low percentage of cover in the tillage system significantly increases water, soil and SOC losses. The high rate of losses observed emphasizes the need to protect the soil in order to conserve its fertility**.** A kinematic wave model for the runoff hydrograph with a variable soil infiltration rate was fitted to the experimental data obtaining good fits to the data of all treatments. The coefficient of determination between measured and fitted data was 0.98.

Keywords: Rain simulator, runoff, erosion, cover crops, olive, kinematic wave model.

II-1. INTRODUCTION

The 97% of the global surface area of olive trees is located in countries in the Mediterranean basin. It is a species well adapted to this climate, where 70-80% of the total annual rainfall occurs in autumn and winter months, and where summers are normally very dry and hot. Olive is not a very demanding crop in terms of water and nutrients, as a consequence of its long adaptation to adverse environmental conditions usually planted in marginal areas with steep slopes and shallow soils.

Permanent crops are placed in tree planting patterns to better take advantage of the soil resources, leaving the area between the crop lines unprotected. Moreover, to capture more water in the soil profile, the farmer controls weeds, traditionally with agricultural implements. By the mid-twentieth century, light work done by animal traction gave way to an intensification of the work using new agricultural machinery. Excessive tillage has led to the disintegration of soil particles, degradation of soil structure and formation of surface crusts and plough pans that reduce infiltration inducing great runoff volumes (Giráldez, 1997).

About 12.6% of the area of Spain is threatened by the risk of severe, or very severe, erosion, while 34.1% is at medium risk (MMA, 2007). Some studies indicate large losses of soil in olive groves, such as Laguna and Giráldez (1990) who estimated that the annual losses in the olive groves studied were in the range of 60 to 105 Mg ha^{-1}. Raglione *et al.* (1999) measured annual soil losses of 41 Mg ha^{-1}, similar values (40 Mg ha^{-1}) reported Bruggeman *et al.* (2005) in olive groves managed with tillage. Lower data (21.5-25.6 Mg ha^{-1}) were measured by Gómez and Giráldez (2007) and Francia *et al.* (2006) in a tilled and a no-tilled bare soil respectively. Today, erosion is considered the biggest environmental problem in the cultivation of olives (Beaufoy, 2002).

The mineral nutrients of the soil are lost with the runoff, either in soluble form, or adsorbed in the sediment, which implies in-site fertility losses and off-site damage by the spread of pollutants in the watershed.

Factors that influence soil loss are the intensity of rainfall events and the inclination and length of slope. The existence of a living or inert cover crop, breaking the uniformity of the surface, reduces the impact of rain on the ground as well as the increase of surface flow, reducing its velocity and favouring infiltration. Gómez and Fereres (2006) obtained reductions in soil loss of more than 50% with cover crops compared to conventional tillage. Francia *et al.* (2006), Ordóñez *et al*. (2007), and Rodríguez-Lizana *et al*. (2007) results indicated that cover crops reduce runoff, soil erosion, and nutrient losses, thus contributing to the maintenance of fertility.

The low organic matter content of Mediterranean soils is an important factor which affects the runoff-erosion process. It is also an essential element in soil fertility. An increase in its proportion makes the soil more permeable, thereby reducing the flow of surface water and soil loss. The removal of cover crops and other plant residues decreases the soil organic carbon (SOC), increasing soil erodibility.

Crop rotation is a practice that is not only recommended in extensive field crops but also in cover crops (Alcántara *et al.*, 2009), since the continued use of the same type or family of crop does not take the most of all the resources in the system, and can produce compaction and other problems. There are only a few studies with different types of cover crop from an environmental point of view, and those studies carried out in the same farm on homogeneous terrain that show the effect on erosion and SOC loss of different species used as cover crops are very scarce.

The use of a rainfall simulator allows the exploration of the efficiency of the different plant types as cover crop. The introduction of physical-mathematical models to describe surface runoff flow, under controlled conditions, could be adopted to estimate the values of soil parameters and their modification by the different agricultural conservation practices.

The kinematic wave model, a simplification of the Saint-Venant equations for the open channel flow, is considered a good tool for interpreting soil and water losses in erosion experiments. Laguna and Giráldez (1993) adapted the model initially proposed by Singh and Regl (1983) carrying on a sensitivity analysis in a similar experiment with rainfall rate constant. They estimated the hydrograph parameters assuming a constant soil water infiltration rate. Under this hypothesis when the equilibrium is reached the flow rate remains constant during the steady-state period. In the circumstances of the Laguna and Giráldez (1993) experiments, with a shallow soil, the model was well fitted to the experimental data. Nevertheless the infiltration rate of water into soil changes with time in most of the cases. Smith and Parlange (1978) developed an equation for the infiltration of water into the soil which was similar to the simplified Green and Ampt equation of wide use in hydrological studies. In fact they demonstrated that both their equation and the Green and Ampt equations can be deduced from a general infiltration equation by the value of a single parameter. Giráldez and Woolhiser (1996) obtained an analytical solution to the kinematic wave equations for the Smith and Parlange (1978) infiltration model, but they did not apply it to any experimental data.

The first aim of this study was to determine the effect of cover crops and rainfall intensity on runoff, sediment yield and associated SOC losses, using a sprinkler rainfall simulator and comparing different species as cover crop.

The second aim of this article was adoption of the kinematic wave model of Giráldez and Woolhiser (1996) to the experimental runoff data of the simulated rain plots adopting the Smith and Parlange (1978) formulation for a variable infiltration rate.

II-2. MATERIALS AND METHODS

II-2.1. Experimental plots

Several rectangular experimental plots were used, 5×10 m^2 in size, located on a 20% slope in the IFAPA "Alameda del Obispo" Experiment Station in Cordoba, in a 6×5 m^2 plantation pattern of olive trees (Fig. 1). The plots had a runoff and sediments collection channel at their lower side, draining the flow through a PVC pipe into a gauge based on the tipping bucket design of Barfield and Hirschi (1986).

The soil of the experimental plots is a Calcixerept Inceptisol, according to Soil Survey Staff (1999). The Table II-1 shows some physicochemical characteristics of the soil.

Table II-1. Physicochemical characteristics of the soil used in the trial.

Depth	pH	pH	CO_3^{-2}	CEC	Sand	Silt	Clay	Textural	OM
cm	*in* H_2O	*in* $CaCl_2$	*%*	$Mol_c\,kg^{-1}$	*%*	*%*	*%*	Class	*%*
0-20	8.61	7.79	19.34	0.15	47.34	34.71	17.94	Loam	2.07
20-40	8.57	7.88	23.60	0.14	49.29	30.88	19.83	Loam	1.07
40-60	8.59	7.89	20.52	0.15	49.04	32.57	18.39	Loam	0.92

CEC: Cation Exchange Capacity; OM: Organic Matter.

Traditional tillage was compared to live planted or spontaneous cover crops as soil management systems. For the sown cover crops, a family of grasses (*Brachypodium distachyon*) was chosen because their good ground protection and ease of handling make them suitable species for cover crops. *Sinapis alba* L. subsp. *mairei* (H. Lindb. Fil.) Maire was chosen as a cruciferous plant; cruciferous plants are a species known by farmers because they usually form part of the spontaneous flora in olive groves, but also are very important for their disease control potential, especially *Verticillium dahliae* (Cabeza-Fernández and Bejarano-Alcázar, 2008) currently under study. Legumes are relevant from the agricultural point of view due to their ability to fix atmospheric nitrogen through symbiosis with *Rhizobium* bacteria. The decomposition of their remains, either left on the surface or incorporated into the soil, provide part of the N requirements for the crop (Guzmán and Alonso, 2001), acting as green manure. Two of the most commonly used species: *Vicia sativa* and *Vicia ervilia*, were choosed for this work. *Brachypodium distachyon* and the leguminous were sown at a rate of 100 kg ha^{-1} of cover. *Sinapis alba* was sown and buried 0.5 cm deep following the procedures established in previous field studies (Alcántara *et al.*, 2009) at a rate of 10 kg per ha of cover.

In one of the plots, the natural flora of the area was allowed to grow as a spontaneous grass. The dominant species were identified, which were *Calendula*, *Bromus* and *Hordeum* species. Later in spring after irrigation, other species appeared such as *Avena barbata*, species of the genera *Erodium, Convolvulus arvensis, Crepis vesicaria* and some mallow.

Summing up, there were six treatments: Tillage, *B. distachyon, S. alba, V. sativa*, *V. ervilia* and spontaneous weeds. The tillage was performed with rototiller 20 cm at depth.

II-2.2. Rainfall simulator

In order to compare the losses, a rainfall simulator was used, consisting of a series of sectorial sprinklers, placed on lateral line on either side of each of the plots, with 3 sprinkler heads per lateral line located on supports 3 m in height (Fig. II-1). By varying the pressure, different flows were obtained, with the possibility of changing the intensity of the simulated rainfall.

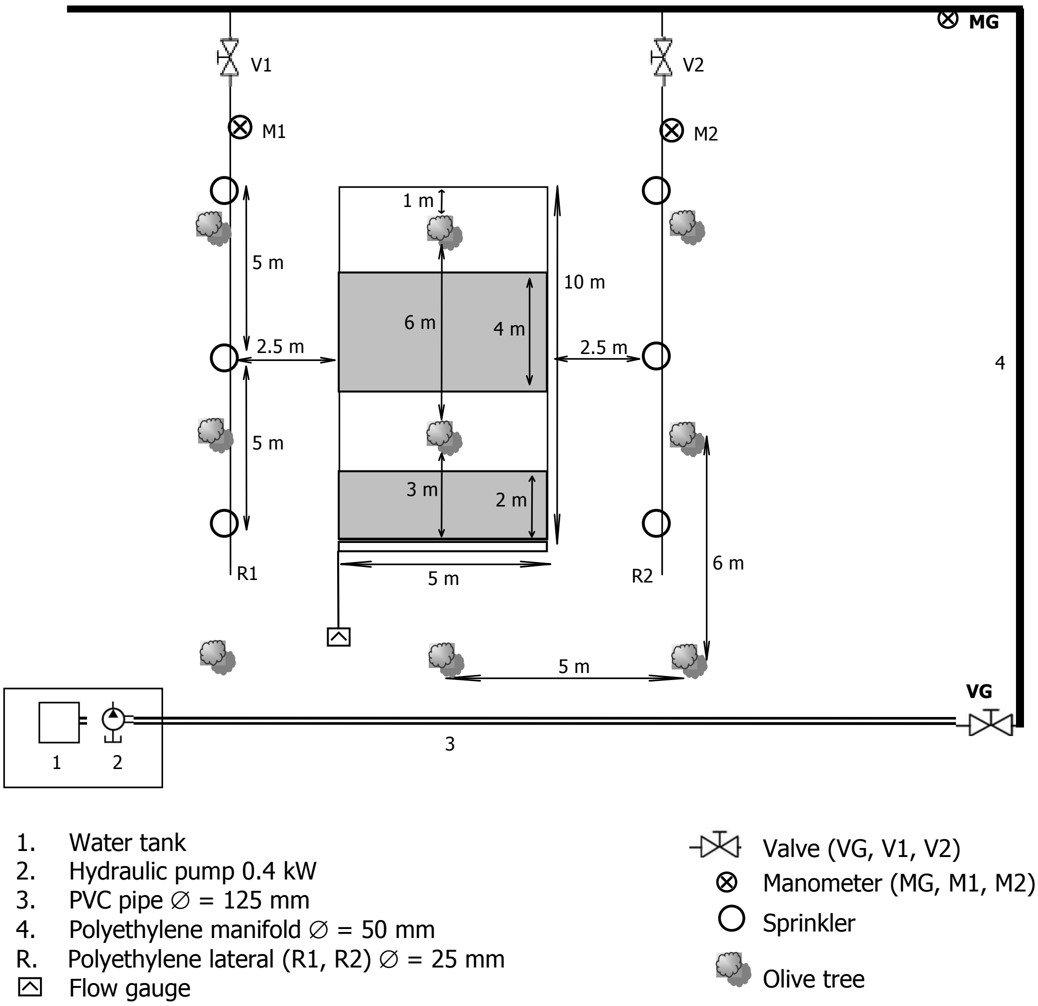


Fig. II-1. Sketch of the rain simulator and the runoff plot.

Twelve simulations for each plot and year were carried out, grouped into 2 series: with cover in its development and after mechanical mowing. In each series two intensities of rain were used: 40 mm h^{-1} (for 90 min before mowing and 120 min after mowing) and 15 mm h^{-1} (for 3 h) and three repetitions were carried out on each plot. The experiment was conducted over two years.

II-2.3. Sampling and analysis

Although previous tests were carried out to check the rainfall was homogeneous across the plot area and intensity was that determined, 8 rain gauges were used during each simulation to check the actual intensity of the trial. The Christiansen uniformity coefficient (unity minus the average absolute deviation from the mean depth divided by the mean depth) was used to evaluate the rain uniformity. Runoff generated was measured with the flow gauge. Erosion was evaluated by a periodic sample of the runoff which was weighed, oven dried, and weighed again to get the sediment mass and the volume. The sediment accumulated in the runoff channel was also collected at the end of the trial. The SOC loss was calculated analyzing the percentage of organic Carbon in sediment samples.

The determination of organic C is based on the Walkley-Black chromic acid wet oxidation method. Oxidisable matter in the soil is oxidised by 1N $K_2Cr_2O_7$ 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 organic C present in the soil sample (Sparks *et al*. 1996)

The percentage of cover was measured by the method of Agrela *et al*. (2003), which consists of estimating the percentage of covered soil in each of the 100 grids each 0.01 m^2 in size divided up in a 1 m^2 frame, using a scale of 0 to 5. The coverage of a plot was calculated as the average of 10 selected points at every series.

The plots were irrigated two days before each run to reach saturation. To check the initial homogeneity in the plots, depth soil samples were taken before each test using an Edelman auger to measure moisture by the gravimetric method. Four depth intervals were taken: 0-5, 5-20, 20-40 and 40-60 cm in three points of each plot.

II-2.4. Kinematic wave model

The model based on the kinematic wave approximation of the Saint-Venant equations:

$$\frac{\partial h}{\partial t}+\frac{\partial q}{\partial x}=r-f \qquad [1]$$

The equation [1] is the mass conservation expression for the water, where h is the water depth, t time, x space, and q, r and f are the overland flow, rainfall and infiltration rates respectively.

The relationship between water depth and flow rate constitutes the momentum conservation equation, reduced to a uniform flow equation:

$$q=\alpha h^m \qquad [2]$$

The α coefficient related to any uniform flow equation such as Manning's or Chezy's, expressing surface conditions, with the m exponent.

By substituting eq. [2] in [1]:

$$\frac{\partial h}{\partial t}+\frac{\partial}{\partial x}\left(\alpha h^m\right)=r-f \qquad [3]$$

$$\frac{\partial h}{\partial t}+\left(\alpha m h^{m-1}\right)\frac{\partial h}{\partial x}=r-f \qquad [4]$$

The term $\alpha m h^{m-1}$ represents the *celerity of the wave*.

Initial and boundary conditions of surface flow were null water depth:

$$h(0, t) = h(x, 0) = 0 \qquad [5]$$

These equations can be solved by the method of characteristics (Courant and Hilbert, 1962), which converts the partial differential equations to a pair of ordinary differential equations, expressing the absolute time variation of the water depth

$$\frac{dh}{dt}=r-f \qquad [6]$$

along the characteristic curves whose equation is

$$\frac{dx}{dt}=\alpha m h^{m-1} \qquad [7]$$

For any rainfall rate starting at time $t = 0$, runoff begins to flow at ponding time t_p, defined by Smith and Parlange (1978) as:

$$t_p=\frac{S^2}{2rKs}ln\left(\frac{r}{r-K_s}\right) \qquad [8]$$

S is the sorptivity and K_s the saturated hydraulic conductivity of the soil.

The infiltration rate, *f*, according to Smith and Parlange (1978), is an implicit equation given by:

$$t - t_p = \frac{S^2/2}{K_s^2}\left[ln\left(\frac{r-K_s}{r}\frac{f}{f-K_s}\right) - \frac{K_s}{f} - \frac{K_s}{r}\right] \qquad [9]$$

The equation for the characteristic curve is found by integration of equation (7)

$$\int_{x_0}^{x} dx = m\alpha\int_{t_p}^{t} h^{m-1}dt = m\alpha\int_{0}^{h}\frac{h^{m-1}dh}{r-f}$$

$$x - x_0 = -m\alpha\frac{S^2}{2}\int_{f}^{r}\frac{h^{m-1}df}{f^2(f-K_s)} \qquad [10]$$

The integral of equation (11) was numerically evaluated with the Gauss-Legendre scheme. The parameters (K_s, $S^2/2$, m and α) were estimated by optimization using Rosenbrock algorithm (Press *et al.*, 2007). The goodness of the fit was calculated with the Nash and Sutcliffe efficiency (E_{NS}) (Krause *et al.*, 2005), which compares the observed (q_{obs_i}) and calculated (q_{cal_i}) values, being $\overline{q_{obs}}$ the average for the observed flows:

$$E_{NS} = 1 - \frac{\sum_{i=1}^{n}\left(q_{obs_i} - q_{cal_i}\right)^2}{\sum_{i=1}^{n}\left(q_{obs_i} - \overline{q_{obs}}\right)^2} \qquad [11]$$

II-3. RESULTS AND DISCUSSION

II-3.1 Runoff, Soil and SOC losses

The real rain rates obtained in each plot and simulation runs are shown in table II-2. The values obtained were slightly different to 40 and 15 mm h^{-1} established previously. The averages for high and low rain rates were 38.75 and 18.06 mm h^{-1} respectively. Significant differences were not found between treatments.

The averages of the Christiansen Uniformity Coefficient in the three repetitions per each simulations series are shown in table II-2. The high values indicate the good homogeneity of the rainfall simulations.

Table II-2. Real rate rain obtained (r) and Christiansen Uniformity Coefficient (CUC) in each plot for the different simulation runs and treatments over the two years of study. B: Before mowing, A: After mowing.

Year	B/A	Rain	TILLAGE		*B. distachyon*		*S. alba*		*V. sativa*		*V. ervilia*		SPONTAN.	
	mowing	rate (mm h^{-1})	r (mm h^{-1})	CUC (%)	r (mm h^{-1})	CUC (%)	r (mm h^{-1})	CUC (%)	r (mm h^{-1})	CUC (%)	r (mm h^{-1})	CUC (%)	r (mm h^{-1})	CUC (%)
1	B	40	37.69	92.12	38.00	90.10	37.40	89.53	39.79	88.36	39.74	92.37	40.78	90.52
	B	15	16.73	90.37	17.67	89.13	17.23	84.32	17.36	83.12	18.09	78.69	18.97	87.92
	A	15	19.50	91.14	18.59	89.21	17.45	77.05	18.49	83.18	18.10	83.69	19.78	87.41
	A	40	38.83	95.88	40.06	96.43	40.22	96.47	36.63	92.61	36.16	92.36	39.44	93.82
2	B	40	35.54	78.94	37.32	88.47	38.06	89.65	41.03	91.80	41.36	95.58	39.65	93.94
	B	15	18.98	89.51	18.42	87.03	18.56	81.32	17.68	88.68	18.38	89.99	16.94	91.97
	A	15	20.72	87.02	18.64	84.00	19.95	81.47	15.57	86.05	15.99	90.93	15.67	86.26
	A	40	39.16	89.91	39.86	93.72	36.79	85.31	37.36	90.97	38.46	89.21	40.56	92.03

In spite of all plots were irrigated with the same volume, the type and develop of cover and the day of year conditioned the initial soil moisture (Table II-3).

Table II-3. Gravimetric moisture (kg kg^{-1}) at depth of 0-60 cm in each plot before the simulation runs and treatments over the two years of study. Different letters indicate significant differences between treatments compared with LSD-test ($p \leq 0.05$). B: Before mowing, A: After mowing.

Year	B/A mowing	Rain rate (mm h^{-1})	Duration (h)	Gravimetric moisture (kg kg^{-1})					
				TILLAGE	*B. distachyon*	*S. alba*	*V. sativa*	*V. ervilia*	SPONTAN.
1	B	40	1.5	0.15 a	0.14 a	0.13 a	0.15 a	0.15 a	0.14 a
	B	15	3	0.11 a	0.10 a	0.11 a	0.12 a	0.14 a	0.12 a
	A	15	3	0.13 b	0.10 c	0.10 c	0.14 ab	0.16 a	0.14 ab
	A	40	2	0.12 b	0.11 b	0.10 b	0.16 a	0.16 a	0.15 a
2	B	40	1.5	0.13 ab	0.10 cd	0.09 d	0.16 a	0.15 ab	0.13 bc
	B	15	3	0.13 ab	0.12 b	0.11 c	0.14 a	0.13 ab	0.13 ab
	A	15	3	0.13 b	0.13 b	0.12 c	0.15 a	0.13 b	0.11 c
	A	40	2	0.12 c	0.13 bc	0.11 c	0.15 a	0.14 ab	0.14 a

The average runoff values obtained from the three repetitions in each series are shown in table II-4. In it, the significant differences with tillage can be seen in almost all the series carried out, except in cases where the soil was freshly tilled, in which case infiltration was improved but only down to the plough pan. This happened in the first series of the first year where spontaneous grass and vetch (*V. sativa*) produced a great runoff volume. At the end of the trials after the two years, all sown species reduced the runoff generated by over 70% compared to a tillage system. With respect to the spontaneous grasses, the *Sinapis* cover runoff was significantly lower than those of other types. The extensive root system of the cruciferous plants facilitated infiltration and their good biomass production provided high surface cover.

Table II-4. Runoff (mm) in each plot for the different simulation runs and treatments over the two years of study. Also indicated are the amount of runoff generated in all the tests carried out, and the percentage reductions relative to tillage and relative to spontaneous weeds. Different letters indicate significant differences between species compared with LSD-test ($p \leq 0.05$)

Year	B/A mowing	Rain rate (mm h^{-1})	Duration (h)	RUNOFF (mm)					
				TILLAGE	*B. distachyon*	*S. alba*	*V. sativa*	*V. ervilia*	SPONTAN.
1	B	40	1.5	2.43 b	2.10 b	0.27 b	9.03 a	1.99 b	7,52 a
	B	15	3	0.58 a	0.00 b	0.00 b	0.29 b	0.46 ab	0,42 ab
	A	15	3	2.85 a	0.00 b	0.00 b	0.05 b	0.35 b	0,26 b
	A	40	2	9.98 a	0.22 d	0.15 d	3.29 c	3.76 c	6,81 b
2	B	40	1.5	7.45 a	2.24 b	0.30 b	0.23 b	1.69 b	0,74 b
	B	15	3	2.09 a	0.00 c	0.00 c	0.07 c	0.28 b	0,19 b
	A	15	3	2.84 a	0.27 b	0.01 b	0.01 b	0.02 b	0,16 b
	A	40	2	16.61 a	3.60 b	0.06 b	0.45 b	3.71 b	0,34 b
TOTAL years 1+2				**44.81 a**	**8.42 bc**	**0.79 c**	**13.41 b**	**12.25 bc**	**16.45 b**
% REDUCTION compared to TILLAGE					-81.20	-98.25	-70.08	-72.65	-63.29
% REDUCTION compared to SPONT.				63.29	-48.79	-95.23	-18.50	-25.50	

Soil losses were generally higher in treatments where there was more runoff, although differences were bigger. Regarding tillage, adding all the losses, reduction percentages of over 90% were obtained with any type of cover (Table II-5). Regardless of the plot where tillage was used, *Sinapis* soil losses were statistically lower than *V. sativa* and *B. distachyon*. The last two species experienced developing problems during the first year, which caused major losses especially under the high intensity rainfall.

Table II-5. Soil losses (kg ha-1) in each plot for the different simulation runs in the two years of study. The amount of erosion generated in all the tests carried out and the percentage reductions relative to tillage and relative to spontaneous grass are also shown. Different letters indicate significant differences between species compared with the LSD-test ($p \leq 0.05$). B: Before mowing, A: After mowing.

Year	B/A mowing	Rain rate (mm h^{-1})	Duration (h)	SOIL LOSS (kg ha^{-1})					
				TILLAGE	*B. distachyon*	*S. alba*	*V. sativa*	*V. ervilia*	SPONTAN.
1	B	40	1.5	373.10 a	233.01 ab	6.25 b	275.61 ab	72.81 b	132.82 ab
	B	15	3	44.69 a	0.00 b	0.00 b	6.92 b	5.38 b	5.80 b
	A	15	3	182.80 a	0.00 b	0.00 b	0.30 b	2.31 b	3.63 b
	A	40	2	2462.45 a	3.09 b	5.41 b	9.14 b	12.44 b	55.79 b
2	B	40	1.5	665.71 a	7.07 b	6.84 b	2.23 b	13.47 b	5.73 b
	B	15	3	126.05 a	0.00 c	0.00 c	2.71 b	2.44 b	2.48 b
	A	15	3	150.67 a	4.46 b	0.00 b	1.61 b	0.85 b	3.18 b
	A	40	2	853.29 a	82.89 b	0.17 b	1.66 b	8.01 b	1.78 b
TOTAL years 1+2				**4858.76 a**	**330.53 b**	**18.67 b**	**300.19 b**	**117.71 b**	**211.23 b**
% REDUCTION compared to TILLAGE					-93.20	-99.62	-93.82	-97.58	-95.65
% REDUCTION compared to SPONT.				95.65	36.09	-91.16	29.64	-44.27	

The effect of a cover crop, either sown or spontaneous, is greater regarding soil loss than in terms of runoff. In runoff generation, the characteristics of the species may be more decisive, and in addition, newly tilled soil may still have good infiltration although the loss of flow has a higher sediment load.

Fig. II-2 shows the relationship between runoff and sediment yield of every simulation. The values corresponding to the tilled plot are usually larger in runoff but mainly in erosion, the points from tillage are represented over the rest (Fig. II-2).

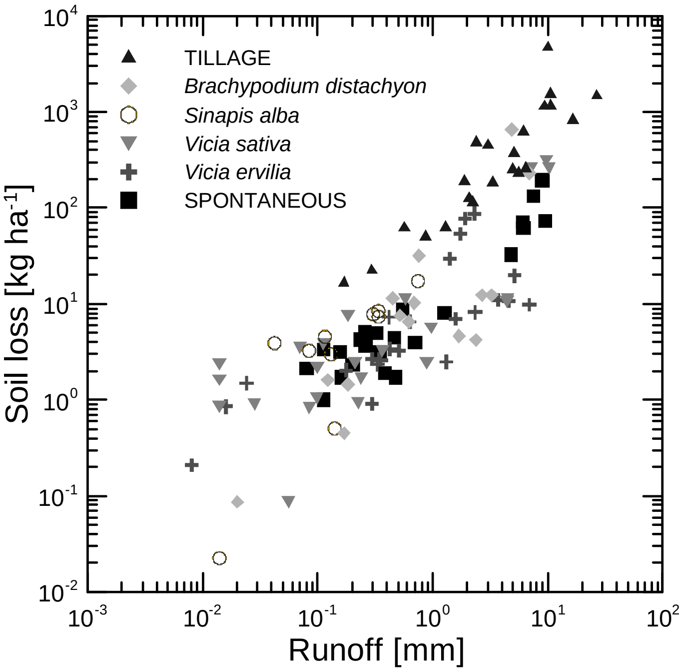


Fig. II-2. Relationship between runoff and soil loss for all treatments and replications.

SOC loss was higher in treatments where soil loss was higher (Table II-6). Occasionally, the low content of organic matter in tilled soils can result in lower loss compared to soil that is richer, especially with rain events that are not very erosive. Fig. 3 represents the percentage of organic carbon in sediment and the soil loss. The data show a descending trend with increasing erosion. The contents of organic carbon in the sediments from tillage plot are usually lower than in cover treatments, especially in events with high erosion (Fig. II-3).

Table II-6. SOC losses (kg ha^{-1}) in each plot for the different simulation runs and treatments during the two years of study. The SOC losses generated across all the tests performed and the percentage reductions relative to tillage and relative to spontaneous weeds are also shown. Different letters indicate significant differences between species compared with the LSD-test ($p \leq 0.05$). B: Before mowing, A: After mowing.

Year	B/A mowing	Rain rate (mm h^{-1})	Duration (h)	SOC LOSS (kg ha^{-1})					
				TILLAGE	*B. distachyon*	*S. alba*	*V. sativa*	*V. ervilia*	SPONTAN.
1	B	40	1.5	6.76 a	2.03 bc	0.14 c	4.59 ab	1.04 bc	3.04 abc
	B	15	3	0.85 a	0.00 b	0.00 b	0.13 b	0.14 b	0.13 b
	A	15	3	6.35 a	0.00 b	0.00 b	0.01 b	0.06 b	0.09 b
	A	40	2	36.45 a	0.16 b	0.07 b	0.22 b	0.35 b	0.80 b
2	B	40	1.5	11.53 a	0.17 b	0.19 b	0.07 b	0.32 b	0.18 b
	B	15	3	1.96 a	0.00 c	0.00 c	0.14 b	0.12 b	0.12 b
	A	15	3	1.17 a	0.07 b	0.00 b	0.03 b	0.03 b	0.15 b
	A	40	2	8.18 a	1.31 b	0.00 b	0.03 b	0.24 b	0.08 b
TOTAL years 1+2				**73.26 a**	**3.73 bc**	**0.41 c**	**5.21 b**	**2.30 bc**	**4.60 b**
% REDUCTION compared to TILLAGE					-94.91	-99.44	-92.89	-96.86	-93.72
% REDUCTION compared to SPONT.				93.72	-18.89	-91.07	11.78	-49.97	

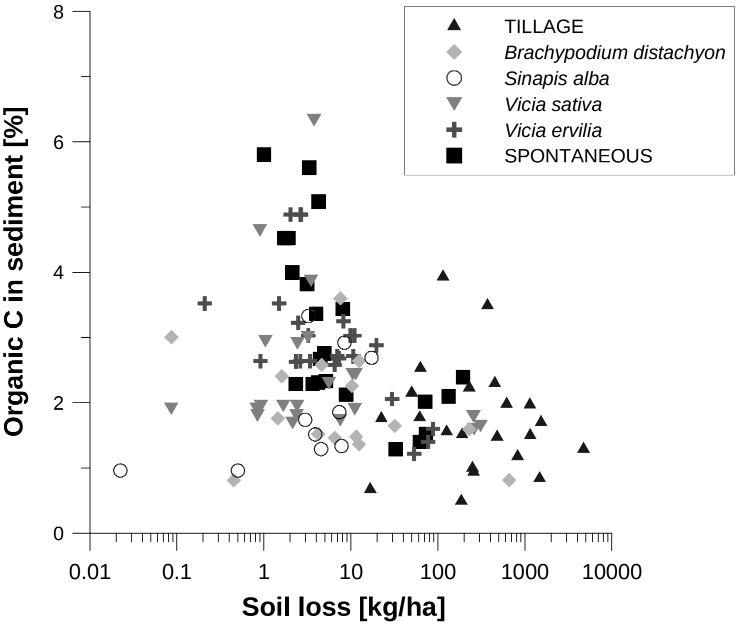


Fig. II-3. Contents of organic carbon in the sediments from each simulation runs and treatments and the soil loss.

Fig. II-4 presents the overall differences between SOC and soil loss between treatments. Worthy of highlight are the cut in the vertical axis and the change of scale to represent the soil loss in tillage plot.

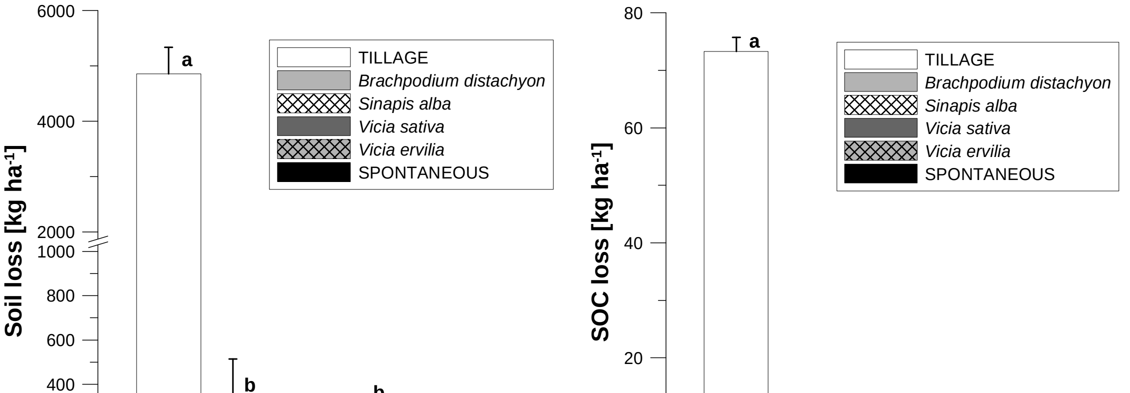


Fig. II-4. Soil and SOC total losses from the simulations performed over two years. Vertical lines represent the Standard Error. Different letters indicate significant differences between species compared with the LSD-test ($p \leq 0.05$).

Our results agree with those obtained by other authors like the 83% reduction of Francia *et al.* (2000) and the 93% of Gómez *et al.* (2009a) respect to a bare soil treatment. Gomez *et al.* (2011) in a comparison between these systems, carried out on grape vines and olive trees, found large reductions in soil loss, SOC and nutrients with different types of seeded and spontaneous cover. Espejo-Pérez *et al.* (2013) reduced erosion by an average of 76% in a study carried out in micro-plots in Andalusian olive groves.

Tillage can lower the organic matter content between 30 and 50% over a few years (Robert *et al.,* 2004). Other authors suggest that losses can reach 60% (Jones *et al.*, 2004). In our simulations, the covers reduced SOC loss by over 90%, percentage greater than those indicated by Marquez-García *et al.* (2013) who found reductions of 80.5 and 67.7% in soil and SOC losses respectively. The reductions of this study are according with those obtained by Gómez *et al*. (2009b) with a *Lolium* cover in bigger plots and lower slope.

II-3.2. Percentage of cover

The sparse crop cover in the tillage system produced greater losses in this plot. The average level of cover over each year is shown in Figure II-5. The period when each series of simulated rainfall was conducted is also shown.

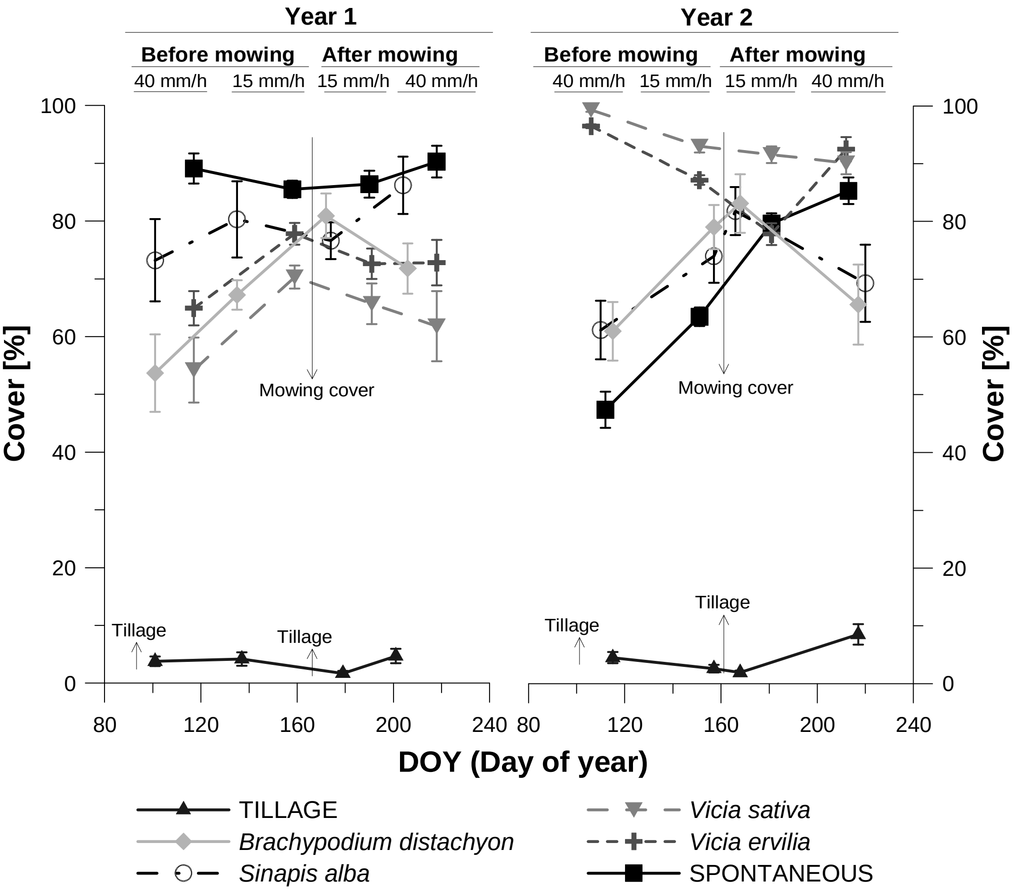


Fig. II-5. Soil surface cover in all simulation runs and day of the year. Vertical lines represent the Standard Error.

After mowing, the surface cover can even increase slightly, given that the erect stems cover less surface than those freshly mowed and left on the ground, though as the remains decompose, the percentage of cover reduces. In some cases such as spontaneous grass, increases can occur due to the onset of summer grasses. Parallel to the mowing in the plots with cover, tillage was carried out in the tilled plot. This plot was tilled before carrying out the series each year. In this type of management the usual practice is to perform at least two tillages over the year.

Figure II-6 compares surface cover with soil and SOC losses. The greatest losses usually correspond to lower cover values, which occur mainly in tillage. The soil and SOC losses are plotted using a logarithmic scale indicating that the differences are larger than those that can be appreciated at first glance.

The cover values obtained with any cover crop loosely exceeded 30% of the covered surface, even after clearing, a threshold that is internationally accepted in conservation agriculture to keep the soil protected (CTIC, 1990).

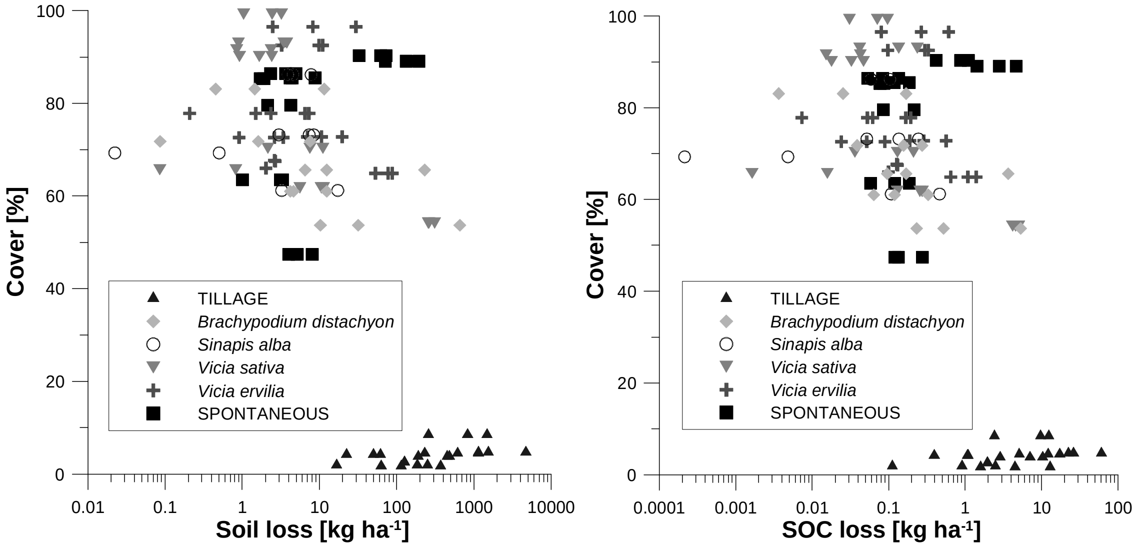


Fig. II-6. Representation in semi logarithmic scale of the individual values of loss of soil and SOC compared to percentage of cover.

II-3.3. Kinematic wave model

The oscillation in the flow data, ought to the tipping bucket, did necessary to choose some data to be able to apply the program.

The model had a good fit to the experimental data, mainly in the tillage plot and high rainfall rate where efficiencies over 0.90 were obtained (Table II-4) except in one case. In the treatments with cover crops, a routine was added to the program because the 2nd domain of the characteristic curve was not always reached.

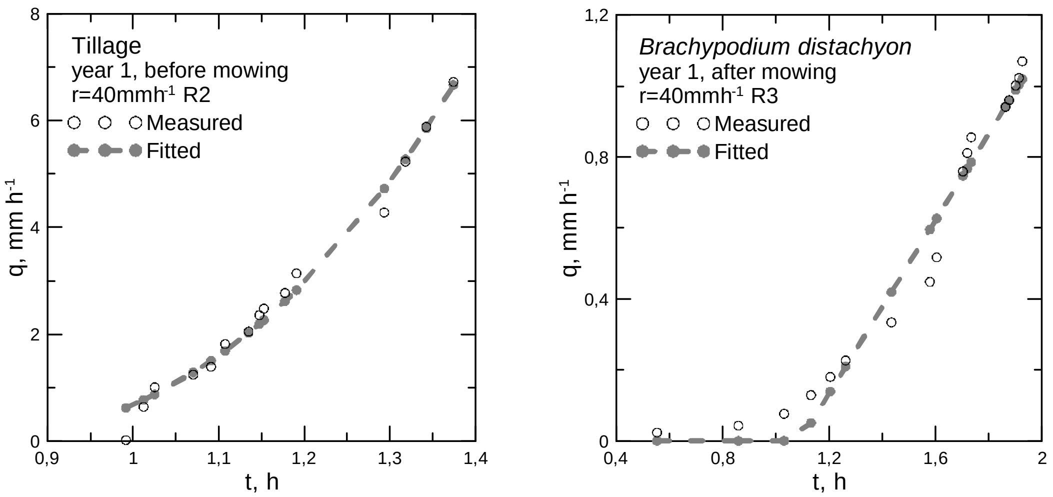
Table II-7. Parameters obtained with the model and efficiency of the fit. B: Before mowing, A: After mowing.

Treatment	Year	B/A mowing	Rain rate mm h^{-1}	Rep.	K_s mm h^{-1}	$S^2/2$ mm^2 h^{-1}	m	α mm^{1-m}h^{-1}	E_{NS}
Tillage	1	B	40	R1	17.22	793	1.61	0.312	0.983
				R2	5.28	788	2.22	0.329	0.985
				R3	17.70	788	1.25	0.621	0.938
Tillage	1	B	15	R1	3.91	397	1.32	0.353	0.949
				R2	3.86	460	1.05	1.806	0.814
				R3	3.90	421	1.16	2.529	0.948
Tillage	1	A	15	R1	2.33	366	3.91	0.022	0.884
				R2	4.25	280	2.75	0.812	0.963

				R3	1.61	366	2.73	0.227	0.886
Tillage	1	A	40	R1	1.83	362	3.12	0.861	0.883
				R2	16.70	491	1.68	0.128	0.955
				R3	33.32	352	1.93	0.542	0.971
Tillage	2	B	40	R1	19.35	609	1.30	0.719	0.963
B.distachyon	1	B	40	R2	20.30	468	2.19	0.161	0.865
				R3	27.97	357	1.97	0.022	0.958
B.distachyon	1	A	40	R3	3.82	213	2.98	0.041	0.973
Sinapis alba	1	B	40	R2	6.20	524	1.33	0.003	0.834
				R3	10.46	524	1.05	0.013	0.933
Sinapis alba	1	A	40	R2	1.08	312	3.72	0.102	0.825
Vicia sativa	1	B	15	R1	7.77	138	1.01	0.253	0.502
Vicia sativa	1	A	40	R1	0.86	67.6	2.97	0.001	0.823
				R3	1.38	102	1.97	0.415	0.644
Vicia ervilia	1	B	15	R1	4.69	118	1.01	0.258	0.842
Vicia ervilia	1	A	15	R1	6.56	24.3	1.01	0.090	0.600
				R2	5.77	128	2.70	0.035	0.963
				R3	4.24	79.8	2.19	0.004	0.843
Spontaneous	1	B	15	R1	9.23	179	1.13	0.090	0.664
Spontaneous	1	A	15	R1	4.55	412	2.21	0.578	0.855
			15	R3	6.40	34.7	1.79	0.017	0.656

All treatments with cover crops got larger values for saturated conductivity (K_s) than tillage in events with 15 mm h^{-1}. This fact indicates a high infiltration in these treatments with low rainfall rate.

One hydrograph chosen from every treatment is shown in the Fig. II-7.



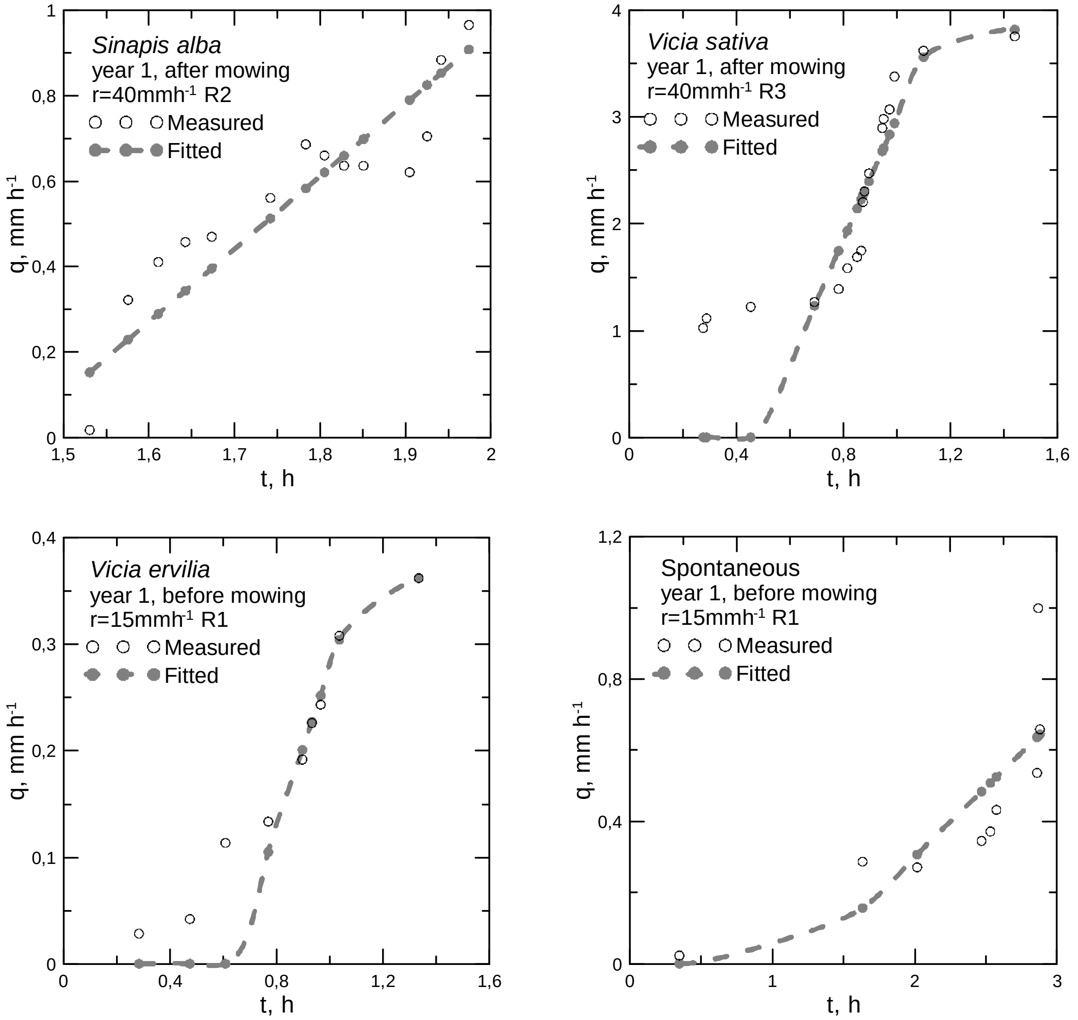


Fig. II-7. Measured and fitted hydrographs for the indicated treatment and run.

A highly significant relationship (R^2=0.98; *p*<0.0001) was found between measured and fitted values (Fig. II-8).

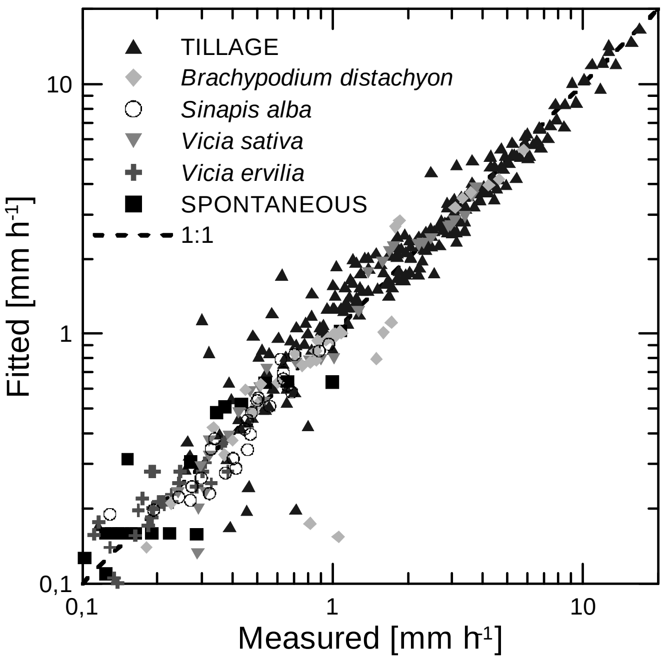


Fig. II-8. Comparison between measured and fitted runoff data.

The good fit indicates the usefulness of this model that has been applied to all treatments with different soil managements providing representative data.

II-4. CONCLUSIONS

The low soil cover of the tillage system significantly increases erosion and SOC loss with respect to the cover crop treatment, with good results obtained irrespective of the plant specie whether it was drilled or natural flora that grew spontaneously. A cruciferous, *Sinapis alba*, was the cover crop that better protected the soil with the lowest runoff, soil and SOC losses.

The rotation of cover crops is recommended to avoid compaction, flora is reversed and to take better advantage of resources and environmental practices. Planting of a species belonging to these three families in a rotation cycle will provide some of the advantages they have, keeping the land protected and reducing losses significantly compared to the tillage system, especially if it is a sloping olive grove, thus maintaining fertility.

The kinematic wave model adopting the Smith and Parlange (1978) solution for variable infiltration rate fits very well to the experimental data of the runoff plots, especially when the soil conditions are homogeneous like a uniformly tilled soil and there are high rainfall rates.

II-ACKNOWLEDGEMENTS

To the field and laboratory personnel of the physics and chemistry soils team at the IFAPA Centre, Alameda del Obispo, for their collaboration in the trials; and to the RTA2010-00026-C02-01 project funded by INIA in the framework of the “National Subprogramme of Agricultural Resources and Technologies with the Autonomous Communities” under the National Plan for Research, Development and Technological Innovation (I+D+I) and co-financed by the European Union via FEDER funds.

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CHAPTER III.

CARBON SEQUESTRATION POTENTIAL OF RESIDUES OF DIFFERENT TYPES OF COVER CROPS IN OLIVE GROVES UNDER MEDITERRANEAN CLIMATE

Repullo-Ruibérriz de Torres, M.A., Carbonell-Bojollo, R., Alcántara-Braña, C., Rodríguez-Lizana, A., Ordóñez-Fernández, R., 2012. Spanish Journal of Agricultural Research 2012, 10, 649-661

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

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(Published in Spanish Journal of Agricultural Research 2012, vol. 10, 649-661)

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III-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.*

Keywords: cover crops, carbon release, 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 2157 y 1666 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 3ª campaña (163 días de descomposición), debido a las condiciones climáticas, se vio restringida la emergencia y el crecimiento de la cubierta. La hierba espontánea liberó la mayor cantidad de C con un valor de 1494 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 7690 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: cubierta vegetal, carbono liberado, fijación de carbono en suelo.

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)

III-1. 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 Common Agricultural Policy (CAP) (EU) 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 and Billbrough, 2004), help to control weeds (Hatcher and 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 and 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.

III-2. MATERIAL AND METHODS

III-2.1. 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 (37º 40' 1.53" N and 4º 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 III-1.

Table III-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

III-2.2. 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.

III-2.3. 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.

III-2.4. 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.

III-2.5. 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 at 65ºC 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).

III-2.6. Cover-residue biomass relation

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

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

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}).

III-2.7. 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…,12*; *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 σ(*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 σ(*AC_strip$_i$*).

III-2.8. 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 $p \leq 0.05$.

III-3. RESULTS

III-3.1. Dynamics of residue biomass

Fig. III-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.

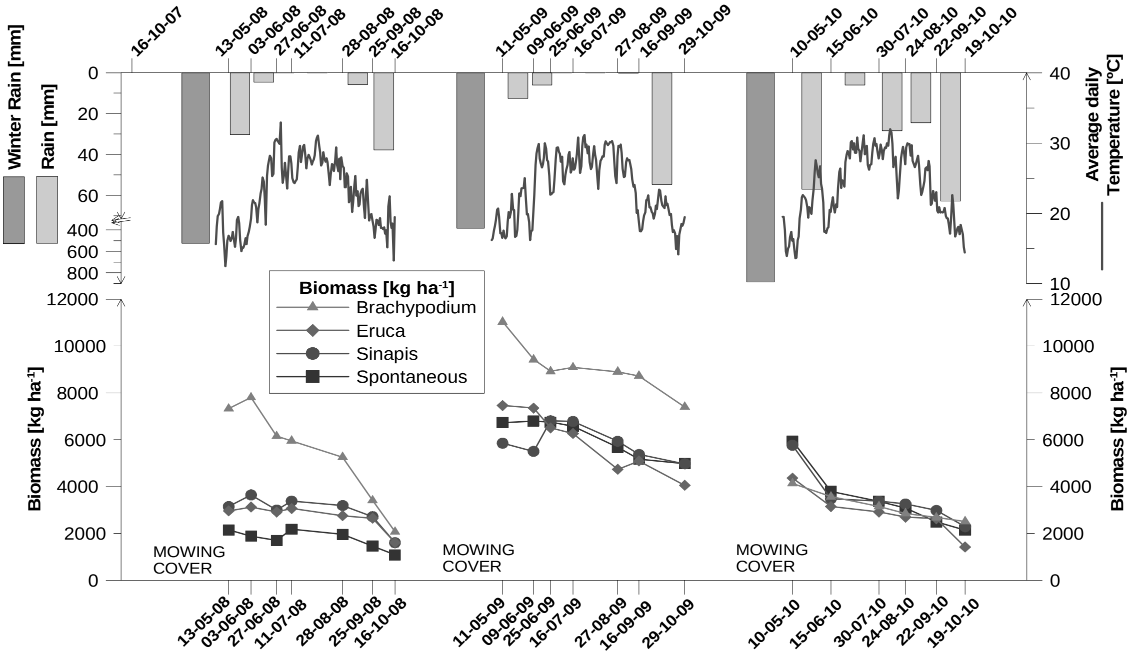


Fig. III-1. Temporal evolution of the climatology and of the residue biomass mean values of the different species and years considered in the study.

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 III-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. III-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 III-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 III-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.

Table III-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≤0.05.

	Brachypodium		***Eruca***		***Sinapis***		**Spontaneous**	
	RB	Cover	RB	Cover	RB	Cover	RB	Cover
Year 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
Year 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
Year 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

III-3.2. Dynamics of residue cover

Fig. III-2 represents the temporal evolution of the percentage of soil cover for the residues of the different species considered. *Brachypodium* cover registers the highest percentage of cover with respect to the rest, with significant differences on all the sampling dates (Table III-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.

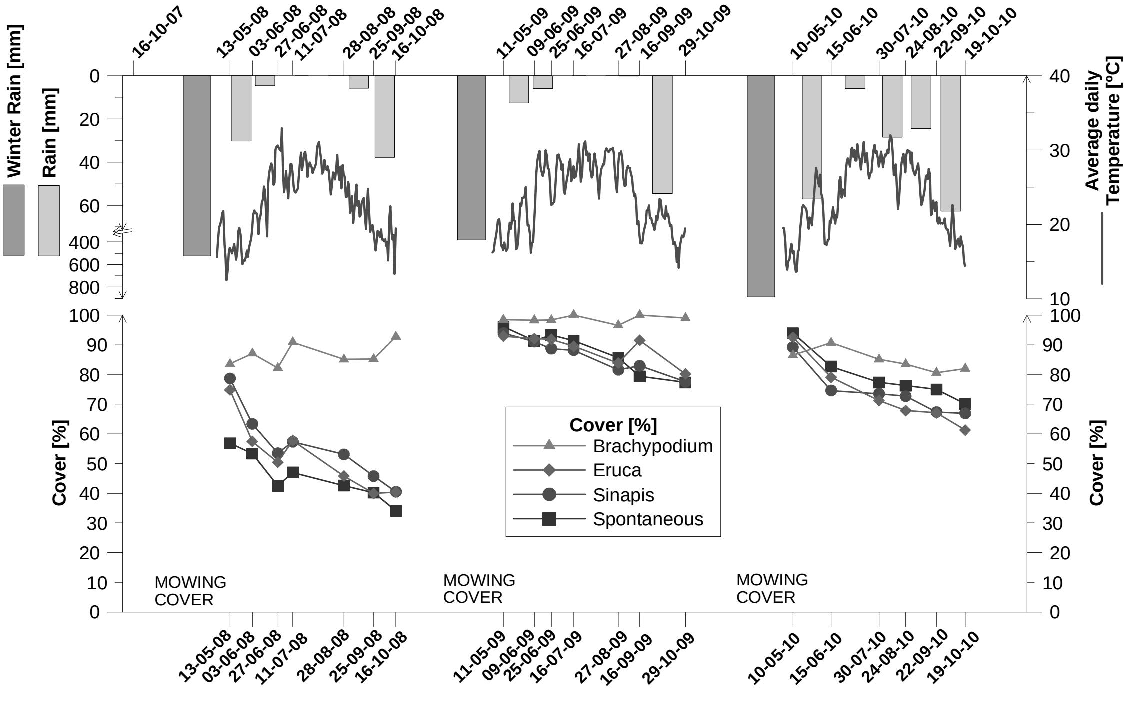


Fig. III-2. Temporal evolution of the cover percentage for the different species and years considered in the study.

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 III-2).

III-3.3. Cover-residue mass relation

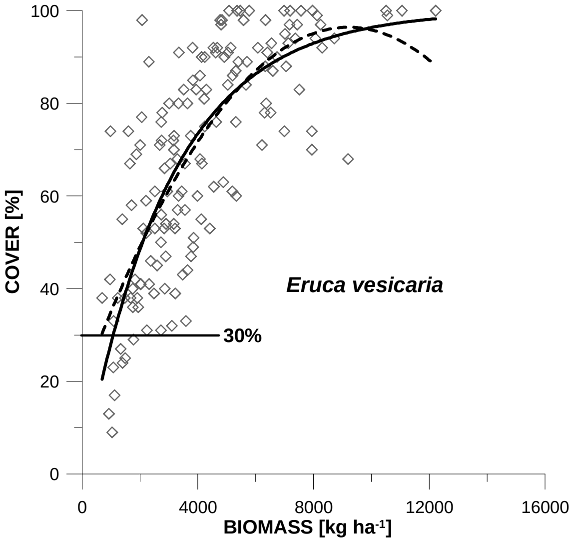
Table III-3 and Fig. III-3 show the result of applying the two models to the relationship between the percentage of soil cover in terms of biomass. The relationship between the soil cover percentage and its biomass was not significant between the variables considered for *Brachypodium*. The high percentage 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*.

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

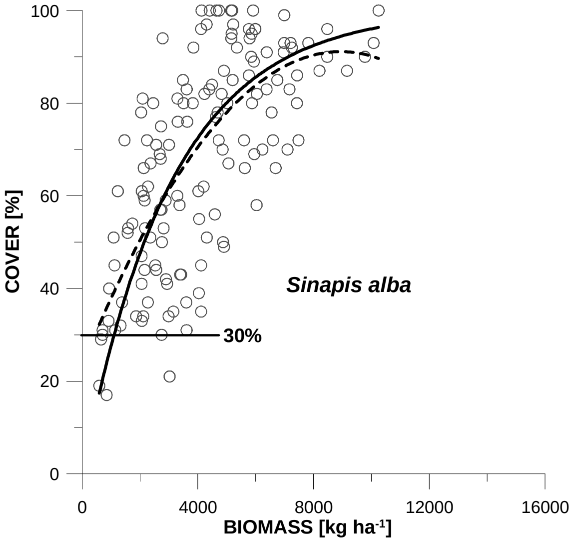
Species	**Model**	**Equation**	R^2	n
Eruca	Quadratic	$Cover_t = 19.184 + 0.0168\, M_t - 9.116 \times 10^{-7}\, M_t^{\,2}$	0.59	155
	Gregory	$Cover_t = 100\,[1 - \exp(-0.000332\, M_t)]$	0.58	155
Sinapis	Quadratic	$Cover_t = 23.615 + 0.0151\, M_t - 8.462 \times 10^{-7}\, M_t^{\,2}$	0.50	144
	Gregory	$Cover_t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

(a)



(b)



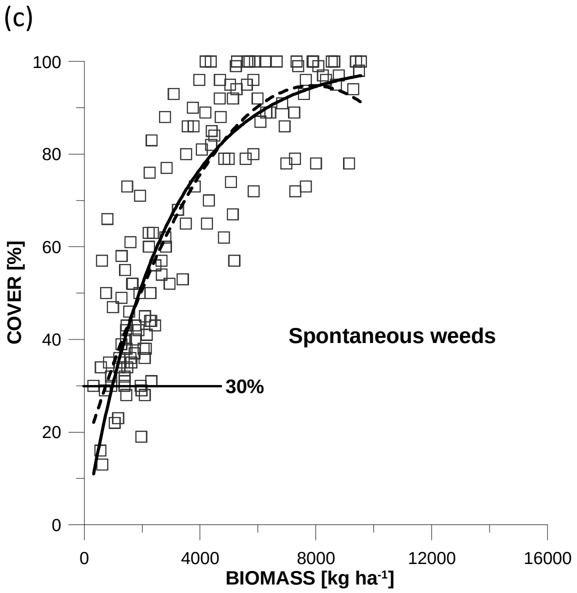


Fig. III-3. Relationship between biomass and cover of (a) Eruca vesicaria, (b) Sinapis alba and (c) spontaneous weeds. The fits are quadratic model (---) and Gregory model (—).

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. III-3 and Table III-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 III-4). The residue mass was piled up covering a portion of soil without being effectively dispersed, and we obtained amounts of residue mass larger in *Eruca* and *Sinapis* than spontaneous weeds.

Table III-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%.

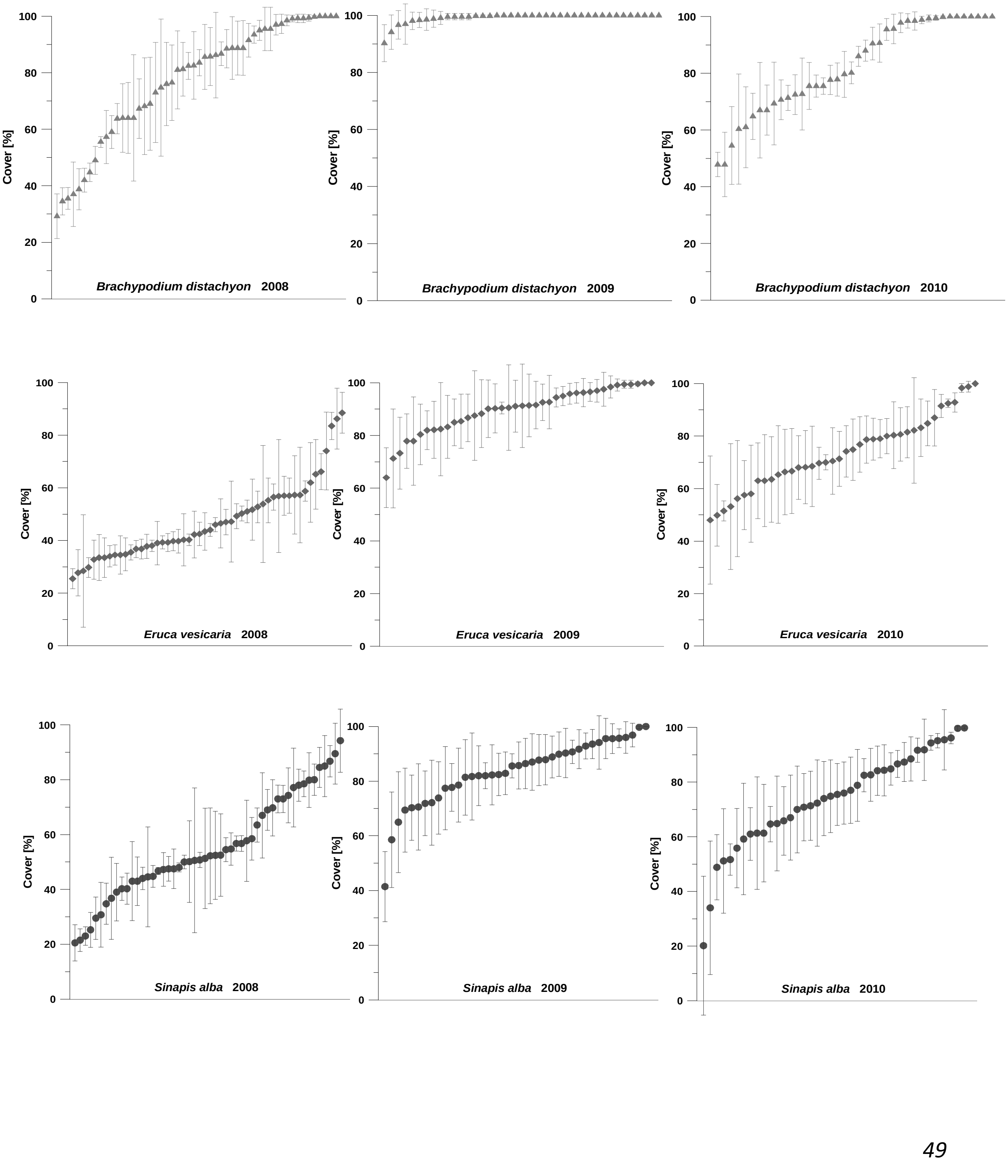
Species	**Biomass (kg ha^{-1})**			
	Quadratic model	**Gregory model**	**Range 25-35%**	**Range 28-32%**
Eruca	668.02	1,074.32	2,167.60	2,461.00
Sinapis	433.37	1,104.26	2,006.29	1,554.97
Spontaneous	746.29	982.58	1,348.72	1,405.33

III-3.4. Spatial-temporal distribution of the residue on the soil

Fig. III-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 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%.



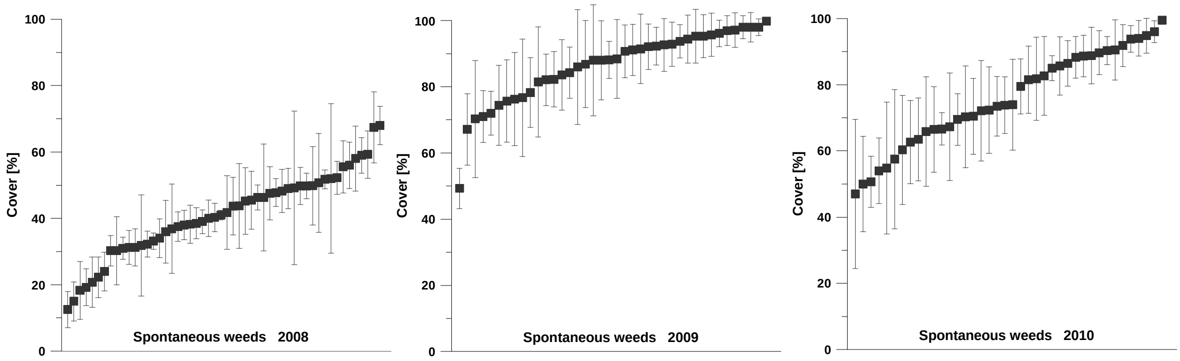


Fig. III-4. Average cover by ranges in the sample strips. Vertical lines represent the standard deviation obtained in each strip.

III-3.5. Release of carbon

Table III-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 III-5).

Table III-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.

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

III-3.6. 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 III-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.

Table III-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≤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

The non alteration of the soil, leaving the cover residues on the surface for three consecutive years, has increased the C content in the different layers of soil considered. Sinapis 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. III-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.

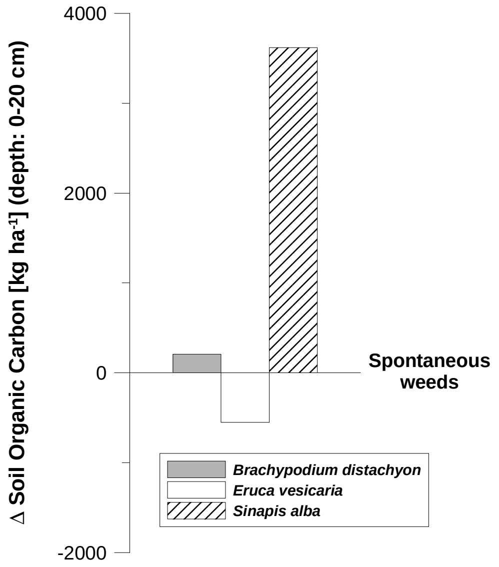


Fig. III-5. Comparison of the quantity of C fixed by different species of plant cover to that fixed by spontaneous weeds in the entire profile of soil (depth: 0-20 cm).

III-4. 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 and 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 and 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 and 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 decomposition of the residue, as well as areas with little cover reducing the level of protection against erosion (Ayed and 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*., 2006).

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 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.

III-ACKNOWLEDGEMENTS

We are grateful to the farmer, F. Alcaraz, for providing his olive orchard farm to carry out the trial; to the field and laboratory personnel of the physics and chemistry of soils team at the

IFAPA Centre, Alameda del Obispo, for their collaboration in the trials; to the Department of Innovation, Science and Enterprises of the Autonomous Government of Andalusia for their financial support through the Project of Excellence RNM 03-205; and to the project RTA2010-00026-C02-01 funded by INIA in the framework of the “National Subprogramme of Agricultural Resources and Technologies with the Autonomous Communities” under the National Plan for Research, Development and Technological Innovation (I+D+I) and co-financed by the European Union via FEDER funds.

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Chapter IV.

Using Olive Pruning Residues to cover soil and improve fertility

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Repullo, M.A., Carbonell, R., Hidalgo, J., Rodríguez-Lizana, A., Ordóñez, R., 2012. Soil and Tillage Research 124, 36-46.

Chapter IV. Using Olive Pruning Residues to cover soil and improve fertility

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(Published in Soil and Tillage Research 2012, vol. 124, 36-46)

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IV-Abstract

The application of organic materials to land is a common practice in sustainable agriculture. The current availability of several types of pruners and choppers on the market has boosted the use of these types of residues as plant cover. Applying these types of residues increases the content of organic matter in the soil, which is very positive for the fertility of the soil and agricultural biodiversity. The latter should be taken into account in ecological olive groves where fertilisation programmes are highly limited. However, no quantitative information is available to provide farmers with a precise assessment.

Experiments were conducted over a period of two agricultural years (2009/10 and 2010/11). Treatments consisted of pruning applications to fine (≤ 8 cm in diameter) and thick (> 8 cm in diameter) in the amounts indicated, I = 2.65 kg m^{-2} fine; II = 2.65 kg m^{-2} fine + 1.12 kg m^{-2} thick; III = 5.30 kg m^{-2} fine; IV = 5.30 kg m^{-2} fine + 2.24 kg m^{-2} thick; and a Control of spontaneous weeds.

The greatest loss of residue mass was recorded at the beginning of the sampling period. The estimated biomass loss in the first six months represented 37-50% of the total. After 704 days of decomposition, the soil maintained cover percentages of 62, 76, 74 and 88% for treatments I, II, III and IV respectively.

The various treatments applied to pruning residues have been more effective at increasing the levels of Soil Organic Matter (SOM) than spontaneous cover. SOM values on the surface (0-5 cm) rose by 0.86, 1.04, 1.28 and 1.52 % for treatments I, II, III and IV in regard to the control treatment, maintaining this improvement in fertility at a depth of 0-20 cm, where SOM increased by 0.43, 0.46, 0.84 and 0.47 % for treatments I, II, III and IV respectively in regard to the control.

Considering all the soil sampled, the largest increase in SOM in regard to the initial content of the soil was achieved by treatment III, which contained the largest amount of fine residues, with 0.63%, compared to increases of 0.33, 0.29, 0.36 and 0.10% for treatments I, II, IV and spontaneous weeds respectively.

Keywords: pruning residues, cover, residue decomposition, carbon release.

IV-1. INTRODUCTION

Andalusia (Spain) is a leader in world olive oil production. This industry is an essential part of the economic activity in over 300 towns and villages in the region. The Andalusia olive industry accounts for 80% of Spanish production, a third of the olive groves in Europe and produces 40% of the olive oil in the world (MARM, 2010).

Olive oil production in Andalusia (Spain) faces two serious problems that have not yet been solved, namely the loss of soil productivity and increasing diffuse pollution due to soil erosion (Rodríguez-Lizana *et al.*, 2007).

The benefits of establishing plant covers for soil protection against erosion and for improving their water balance are associated with the presence of plant remains which maintain a dense cover on the soil for the longest possible time. However, the cover percentage and its permanence over time depend on the type of residue and on the area's climatology (Thorbun *et al.*, 2001).

Some experiments have been carried out on the use of plant covers in woody crops, where the conservation benefits have been shown. Francia *et al.* (2000), in olive tree plots with a 30% slope, indicate a reduction of 83% in the loss of soil with the use of plant covers. Gómez *et al.* (2009) indicate that plant cover reduces 93% of soil loss due to runoff with respect to an olive grove on bare soil. Ordóñez *et al.* (2007a) found that covered soils reduce the effects of erosion in ecological olive orchards by 56% and 80% as compared to conventionally tilled soils. Monteiro and Lopes (2007) and Francia *et al.* (2006) recommend extending the use of cover crops to olive groves and vineyards in Mediterranean areas to improve soil and water conservation.

Apart from the benefits described above, one of the factors that contribute to the increased use of plant covers in olive groves in Mediterranean areas is that more environmental criteria are being incorporated into agricultural policy and Community rural development through The Code of Good Agricultural Practice and, more recently, the single payment system (Calatrava *et al.*, 2011).

Practically all the studies have been performed on live plant covers. However, in rain-fed plantations, these types of cover can compete for water and nutrients with trees. As a result, the modification of other cultural practices is necessary, such as the dose and application time of fertilisers. Although this type of cover improves infiltration (Pastor, 1989), better water balances are obtained by using inert plant covers that do not compete with trees (Márquez, 2007a; Márquez, 2007b). Alcántara *et al.* (2011) indicate the importance of when live cruciferous plant covers are mowed so they do not compete with olive trees for water and nutrients. Moreover, the trees make better use of such plant covers (Welker and Glenn, 1991).

Inert covers include pruning remains, of which the rain-fed Andalusian olive orchards supply similar annual amounts to the harvest of olives (between 1.3 and 3.0 Mg ha^{-1}) (Ordóñez *et al.,* 2007b). Pursuant to current legislation, farmers must take into account Decree 247/2001 (amended by Decree 371/2010), which approves the Regulations to Prevent and Combat Forest Fires, when removing pruning residues.

The decomposition rate of organic residues varies significantly depending on whether they are located on the surface or within the soil (Alvarado, 2006), on their spatial distribution (Khalid *et al*., 2000a; Lim and Zahara, 2000) and on the size of the residues (Khalid *et al.*, 2000b). The size of the residues affects the specific surface in contact with the ground and therefore microbial colonisation and the exchange of water and nutrients with the surrounding soil. In this study, Fruit *et al.* (1999) cited by Guérif *et al.* (2001), indicate that the ideal average for such pruning remains should be between 5 and 15 cm.

Pruning residues decompose and humificate slowly due to their high content of cellulose and lignin, medium to low content of moisture and a high C/N ratio, which makes it possible to ensure long-lasting soil protection (Ramos, 1999).

Most of these residues are usually burnt on the farm requiring a large amount of the labour force. This practice, which is being increasingly controlled by authorities, has several drawbacks, such as the risk of burning olive trees near the bonfire, especially in intensive plantations, and CO_2 emissions into the atmosphere. One additional problem of residue burning is the reduction in C sequestration (Qingren *et al.*, 2010).

Furthermore, in ecological farming systems, fertility management is one of the most important aspects in terms of limiting output (Ostegard, 2002). Ecological agriculture bases the management of soil fertility on organic matter and biological soil processes. As soil organisms are generally heterotrophs, their activity will be particularly relevant when organic matter is readily available.

Olive grove soils generally have a low content of organic matter, a situation which is further aggravated by erosion, mainly due to certain farming practices that have exerted a decisive influence on accelerating this process (Soria *et al.*, 2003). In the Mediterranean region, Álvarez *et al.* (2007) observed that the carbon in the soil could decrease by up to 50% in olive grove soils, compared to natural areas of vegetation nearby.

As regards plant remains, many authors have indicated the benefits of returning the remains of the crops to the soil and their possible utilisation as an organic rectifier, as they enhance soil quality (Franzluebbers, 2002; Sofo *et al.* 2005), the most direct effect being an increase in the organic carbon content of the soil (Chivenge *et al.*, 2007; Mondini *et al.*, 2007).

The objective of this research is to assess the capacity of different pruning residue treatments carried out in olive orchard lanes to increase carbon, in addition to estimating the decomposition dynamics of these plant remains and how their evolution over time affects the cover surface, the biomass of the remains and their capacity as a source of carbon for the soil.

IV-2. MATERIAL AND METHODS

IV-2.1. Field Trials and Experiment Design

Experiments were conducted over a period of two agricultural years (2009/10 and 2010/11) in Alameda del Obispo (Córdoba, Spain) organic olive orchard farm, with picual olive trees that are 40 years old and a plantation frame of 8 x 8 m. The olive trees had a height average of 4.1 m and a canopy diameter of 5.3 m which represents a volume of 9407 m^3 ha^{-1}. The UTM coordinates in the central point of the trial plot are X = 341642 m, Y = 4192085 m, zone = 30 North, with an elevation of 117 m above sea level. The soil is a calcixerept Inceptisol, according to Soil Survey Staff (1999), with some physicochemical characteristics shown in Table IV-1.

Table IV-1. Physicochemical characteristics of olive grove soil used in the trial.

Depth	pH H_2O	pH Cl_2Ca	EC	CEC	Sand	Silt	Clay	Textural class	OM
cm			*dS/m*	*$mol_c\,kg^{-1}$*	*%*	*%*	*%*		*%*
0-20	8.6	7.8	0.1	0.20	41.6	40.6	17.8	Loam	1.9
20-40	8.6	7.8	0.1	0.19	44.5	37.6	17.9	Loam	1.3
40-60	8.8	7.9	0.1	0.17	44.8	37.5	17.7	Loam	1.0

Depth	CO_3^{-2}	NO_3^-	NO_2^-	NH_4^+	P	K^+	Na^+	Ca^{+2}	Mg^{+2}
cm	*%*	*$mg\,kg^{-1}$*	*$mg\,kg^{-1}$*	*$mg\,kg^{-1}$*	*$mg\,kg^{-1}$*	*$mg\,kg^{-1}$*	*$mg\,kg^{-1}$*	*$mg\,kg^{-1}$*	*$mg\,kg^{-1}$*
0-20	16.4	8.0	0.5	1.1	18.4	402.6	36.9	5482.7	125.3
20-40	20.4	5.8	0.6	1.4	14.1	303.6	38.8	5452.0	122.7
40-60	20.9	8.3	0.3	1.6	12.8	205.0	41.7	5337.3	140.0

The experimental unit was a subplot of 28 m^2 and consisted of the distance between 3 olive trees with a cover strip width of 2 m (Figure IV-1). A randomised complete block design with six replications was adopted. The experimental plots were sited perpendicularly to the slope (1.7 %).

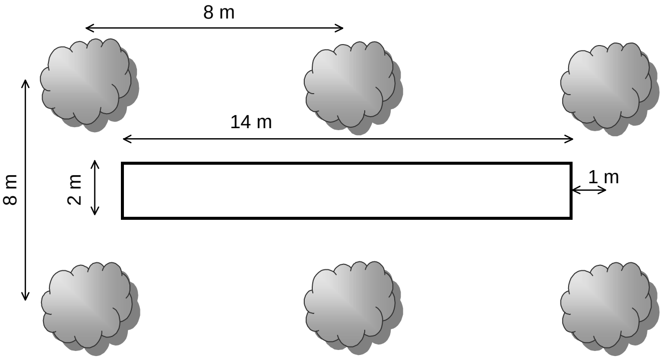


Fig. IV-1. Diagram of a trial subplot.

In order to perform the trial, different olive trees on the farm were pruned and the residues obtained per tree were weighed, differentiating the fine wood (light pruning from the cleaning of the orchard, with a diameter equal to or below 8 cm) from the thick wood (renewal pruning greater than 8 cm in diameter). The average pruning of ten olive trees was measured, obtaining 42.3 (4.4) kg of fine pruning residues and 17.9 (2.4) kg of thick pruning residues per tree. Standard error is indicated in brackets. The olive trees had not been pruned for three years.

In order to include the various chopping options currently available to farmers, two types were distinguished, depending on the size of the residues, namely field treatments with self-fed and hand fed chopping machines. Therefore, two treatments were adopted, namely treatment I (fine residues) and treatment II (fine and thick residues).

In the field, one operation usually carried out during pruning when the residues are subsequently going to be scattered is to occupy half the lanes, so that one lane is left free while the remains from two rows are distributed in the other. For that reason, treatments III (fine residues) and IV (fine and thick residues) have double the remains of treatments I and II. The experiment consisted of pruning applications to fine (< 8 cm in diameter) and thick (> 8 cm in diameter) residues in the amounts indicated: I = 2.65 kg m^{-2} fine; II = 2.65 kg m^{-2} fine + 1.12 kg m^{-2} thick; III = 5.30 kg m^{-2} fine; IV = 5.30 kg m^{-2} fine + 2.24 kg m^{-2} thick and a control of spontaneous weeds that were mowed twice a year.

These amounts per unit of surface were adopted in accordance with the average pruning output of 10 olive trees and the distance between olive trees considering an aisle width of 2 m: 42.3 kg fine pruning per tree / (8 m between olive tree x 2 m of cover strip width) = 2.65 kg fine pruning per m^2; 17.9 kg thick pruning per tree / (8 m between olive x 2 m of cover strip width) = 1.12 kg thick pruning per m^2.

Control subplots were characterised by species and biomass of spontaneous weeds. The control treatment had 1848 kg ha^{-1} of residue mass of spontaneous weeds at the beginning of the experiment. The main annual species of weeds were *Bromus madritensis, Bromus hodeaceus, Avena barbata* and *Hordeum leporinum.* In spring and summer*, Medicago sativa, Convolvulus arvensis, Cyperus rotundus* and *Crepis vesicaria* had been growing mainly, adding about 400 kg ha^{-1} of biomass.

IV-2.2. Sampling

In each treatment and block, an area with a high accumulation of residue was selected. Six pruning residue collection points were established, which made a total of 24 samples per sampling day. The residue mass was estimated from the stubble collected in a metal frame of 0.25 m^2, which served to delimit the sampling area and which was placed at all the points selected. The sampling was carried out on a quarterly basis and as the residue was lignocellulosic with a high C/N ratio that limited decomposition.

Soil samples were taken every two field visits. The same occurred in the case of the pruning residues, that is, six sampling points were considered for each of the five treatments. Samples were taken at a depth of 5 cm. At the end of the second year, soil sampling at depths of 5, 10, 15 and 20 cm was performed to assess the effect of applying the pruning residues at depth. The soil samples were taken with Veihmeyer auger at depth. A cylinder of known volume was used to measure the bulk density.

The cover percentage was estimated following the evaluation per sector method described by Agrela *et al.* (2003), which uses a 1 m^2 frame divided into 100 0.01 m^2 squares and consists of subjectively evaluating 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.

IV-2.3. Analysis of samples

The residue collected was sent to the laboratory, where it was washed with distilled water to prevent contamination in the subsequent analysis and placed in an oven at 65ºC until it reached a constant weight and it was possible to estimate the amount of dry matter. Total carbon and nitrogen was analysed in a LECO elemental analyser.

The soil samples were air-dried and sieved through a 2 mm mesh sieve for their subsequent analysis. In order to determine the percentage of total organic carbon, the method by oxidation with dichromate was used (Sparks *et al.*, 1996).

The amount of Soil Organic Carbon (SOC) was calculated according to equation [1]:

$$SOC\left(\frac{Mg}{ha}\right)=\%\,SOC\left(\frac{kg_{soc}}{100kg_{soil}}\right)\times\rho_b\left(\frac{kg_{soil}}{m^3}\right)\times D(m)\times 10^4\left(\frac{m^2}{ha}\right)\times 10^{-3}\left(\frac{Mg}{kg}\right) \qquad [1]$$

where "ρ_b" is the bulk density of the soil and "*D*" the depth of soil we refer to.

For each treatment (*t*), we calculate the content of carbon accumulated at a given depth (*D*) using equation [2]:

$$SOC_{Dt}\left(\frac{Mg}{ha}\right)=\sum_{1}^{n} SOC_{i}\left(\frac{Mg}{ha}\right) \qquad [2]$$

where "i" is the number of depth intervals sampled.

The increase in soil carbon content for the different treatments was obtained by way of equations [3] and [4]:

$$\Delta SOC_{Dt}\left(\frac{Mg}{ha}\right)=SOC_{final}\left(\frac{Mg}{ha}\right)-SOC_{beginning}\left(\frac{Mg}{ha}\right) \qquad [3]$$

$$\Delta SOC_{Dt}\left(\frac{Mg}{ha}\right)=SOC_{Treat.}\left(\frac{Mg}{ha}\right)-SOC_{Contr.}\left(\frac{Mg}{ha}\right) \qquad [4]$$

Equation [3] provides the increase in regard to the original state, which is calculated as the difference between SOC at the beginning and the end of the period of study for each treatment. Equation [4] determines the difference between a given treatment and the control.

Soil Organic Matter (SOM) was calculated from SOC.

IV-2.4. Decomposition of residues

We have fitted a double exponential decay model (Bunnell and Tait, 1974) [eq. 5], which takes into account the fractions of easy and difficult decomposition. The corresponding equation is as follows:

$$y_t = y_0\, L\, exp(-k_1\, t) + y_0 (1-L)\, exp(-k_2\, t) \qquad [5]$$

where y_t (kg ha^{-1}) is the remaining amount of pruning residues at time *t*; y_0 (kg ha^{-1}) the quantity of remains at the beginning (*t* = 0 days); *L* is the Labile fraction and 1-*L* the difficult decomposition fraction; k_1 and k_2 ($days^{-1}$) are the decay constants of the labile and recalcitrant fraction, respectively and *t* (days) is the time considered.

IV-2.5. Spatial-temporal distribution of pruning residue in the soil

This section evaluates the variability of the percentage of cover under field conditions. For this purpose, 12 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 percentage of cover in the different strips, a similar method 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.

$$AC\_strip_i = \sum_{t=1}^{n} \frac{Cover(\%)_{it}}{n} \qquad [6]$$

with AC_strip_i, mean temporal cover in the strip i; n = samplings done in each treatment of pruning; $i = 1,........,12$; $Cover(\%)_{it}$, cover percentage obtained in the strip i, instant t.

$$\delta\,(AC\_strip_i) = \left[\frac{\sum_{t=1}^{n} \left(Cover(\%)_{it} - AC\_strip_i\right)^2}{n-1} \right]^{1/2} \qquad [7]$$

with $\delta(AC\_strip_i)$ 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 $\delta(AC\_strip_i)$.

IV-2.6. Carbon release

The carbon release rate of the different pruning residue treatments was estimated, understanding as such the difference between the content of this element in the residues when they were incorporated into the soil after pruning and that estimated in the residue samples collected on the different dates, according to equation [8]:

$$Creleased_t = C_0 - C_t \qquad [8]$$

where C_t (kg ha^{-1}) is the amount of carbon remaining in the residue at time *t* and C_0 (kg ha^{-1}) the amount of this element remaining in residues when these were applied to the soil.

The decreases over time were fitted with a single exponential model to the element, as follows:

$$C_t = \alpha_o exp(-k\,t_i) + \varepsilon_i \qquad [9]$$

where C_t is the amount of carbon remaining at time t_i, α_o is the estimated element pool in $t_i = 0$, k (day^{-1}) is the carbon release rate constant, t_i is the time (in days after pruning), and ε_i is the random error.

IV-2.7. Data analysis

We controlled the weather in the area during the two-year study, assessing rainfall and maximum and minimum daily temperature data. The data are taken from a weather station located 500 m from the experimental plot, which belongs to the network of agricultural weather stations (RIA) of the Andalusia Regional Ministry of Agriculture and Fisheries (Spain).

On each of the sampling days a variance analysis was performed using a random block design, the dependent variables of which were the quantity of residues on the surface and the percentage of cover. The subsequent comparison of means was undertaken using the Tukey's test ($p \leq 0.05$)

Percentages of OC remaining at each sampling were regressed in time using the non-linear regression model procedure of SPSS 12. The double exponential model was fitted to the data using the non-linear regression model provided by the Statistix 9.0 programme.

IV-3. RESULTS AND DISCUSSION

IV-3.1. Residue mass and C/N ratio

Figure IV-2 represents the temporal evolution of the residue mass in the different pruning residue treatments considered in the study, as well as the temperature and rainfall recorded during the two-year sample period.

The greatest loss of residue mass was recorded at the beginning of the sampling period. In fact, mass loss in the first six months amounted to 45%, 48%, 37% and 42% of the total estimated in I, II, III and IV treatments respectively, in the 704 days that the residues covered the soil. Similar results were obtained with pruning residues in alley cropping by Youkhana and Idol (2009), although with other species and climate. During the decomposition of lignocellulosic residues, as is the case here, there is an initial stage of rapid biomass loss due to soluble compounds being washed and the decay of labile matter (e.g. sugars, some phenols, starches and proteins), followed by a slower second stage resulting from the decay of recalcitrant elements such as cellulose, hemicelluloses, tannins and lignin (Arellano *et al.*, 2004; Goma-Tchimbakala and Bernhard-Reversat, 2006).

After this period of time, the residues decompose very slowly, biomass losses of only 2% and 10% being recorded in the samplings made in the following 12 months regardless of the treatment considered. The high proportion of remains applied in treatment IV maintained biomass values above those registered in the rest of treatments, recording significant differences of $p \leq 0.05$ on all the days sampling was performed.

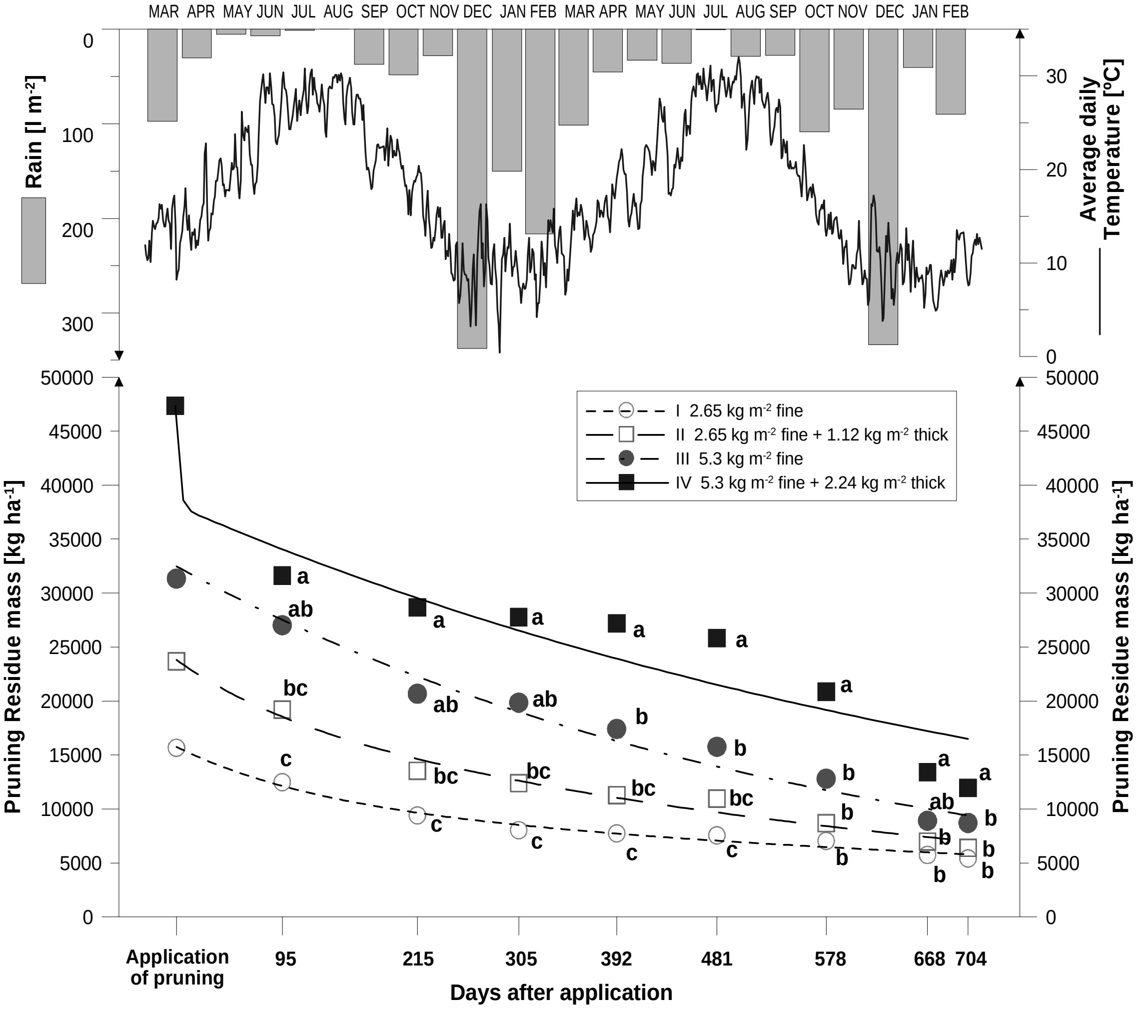


Fig. IV-2. Temporal evolution of rainfall, air temperature and kg of residue mass per ha of cover in the different pruning residue treatments considered in the study. Different letters on a specific date indicate significant differences compared with Tukey's test p≤0.05. The represented fit is a double exponential model.

The C/N ratio can be used to explain the quality of the plant residue that is applied to the soil in regard to movement ratios (Tejada *et al.*, 2009); Tian (1992) states that it is the main indicator of microbial activity. Figure 3 shows the percentage of remaining residue mass depending on the C/N ratio and the percentage of N in the remains for the different treatments and sampling dates. The best ratio is observed in the treatments with the least amount of remains, namely treatments I and II, which also record the highest coefficients of determination. In the case of treatments III and IV, the fact that more residues were applied has had a greater impact on their evolution than the weather conditions or their composition (Figure IV-3). Furthermore, it is worth indicating that for one same percentage of remaining pruning residue mass, the treatments with only fine residues (I and III) have more content of N and a lower C/N ratio, which is logical considering the matter is less lignified.

Authors such as Barajas-Guzmán and Álvarez-Sánchez (2003) and Arrigo *et al.* (2005) point out that excess plant residues applied to the soil can produce anaerobic conditions that limit residue decay. This situation facilitates the concentration of some of the indicators of soil quality, such as lignin, cellulose, nitrogen and carbon, relating such changes to the colonisation and activity of decomposing organisms.

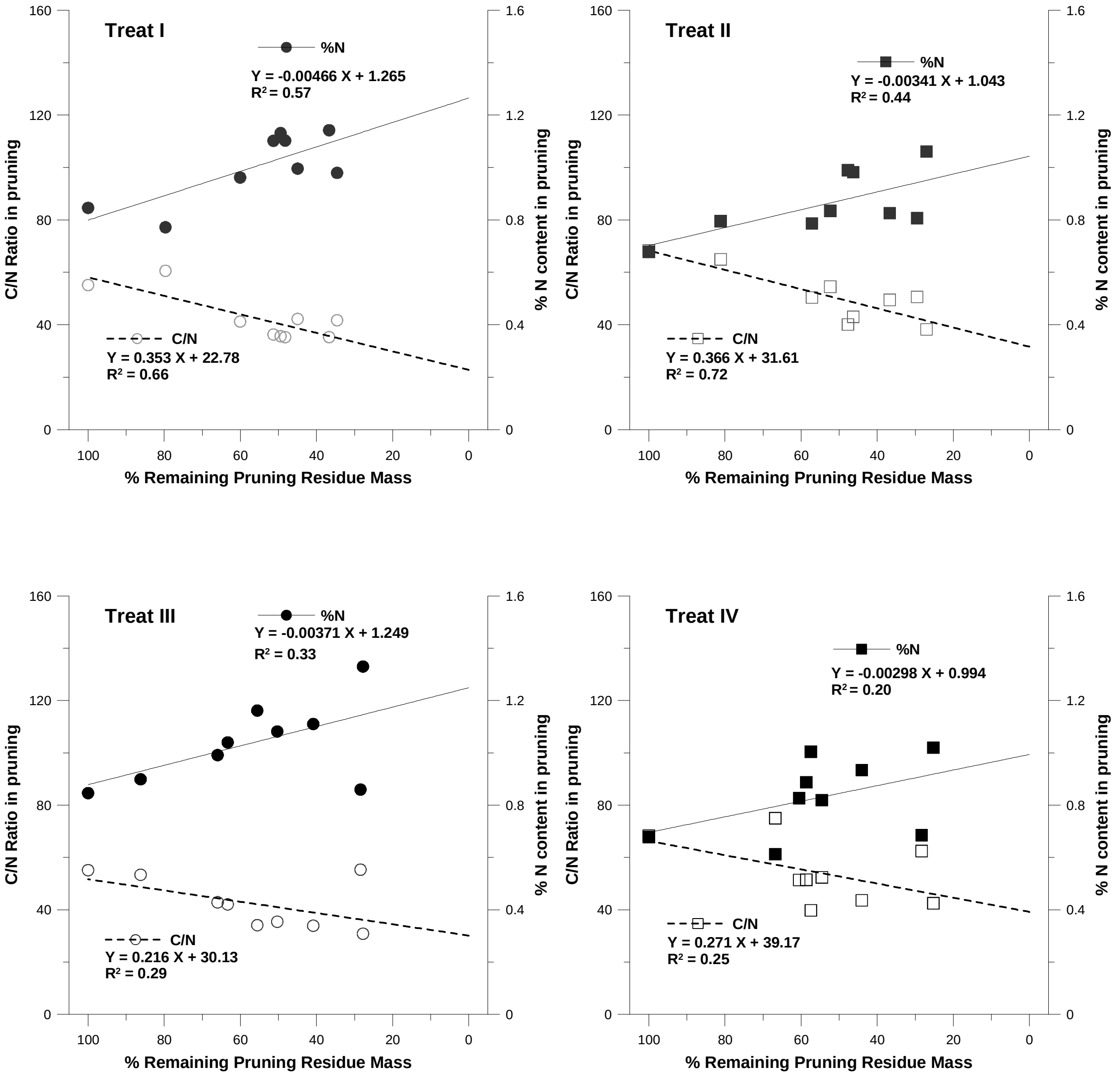


Fig. IV-3 I), II), III) and IV). Percentage of remaining pruning residue mass and percentage of N content and C/N ratio in pruning.

Treatment IV recorded the largest loss of biomass, namely 35404 kg ha^{-1}, followed by doses II (17278 kg ha^{-1}), III (12635 kg ha^{-1}) and I (10252 kg ha^{-1}). However, the overall loss percentage for the 704 days in total was similar for all doses, the percentage of remaining residue mass was between 25% for treatment IV and 35% for I (Fig. IV-7).

The decomposition dynamics of the pruning residue mass have been fitted to a double exponential model. This type of model is related to the presence of various chemical constituents of differing resistance to degradation contained in the material, with the readily decomposable ones disappearing rapidly and the more resistant constituents remaining.

All treatments fit the model well with coefficients of determination close to unity (Table IV-2). A larger labile fraction is obtained from the statistical fit for the treatments of only fine residues (I and II), which is reasonable considering the plant matter is younger. In all treatments, the constant k_1 which regulates the decomposition of the labile fraction is greater than k_2 which includes the evolution of recalcitrant compounds.

The labile fraction is made up of water-soluble substances and polysaccharides that are readily biodegraded by the bacteria and fungi that act in the initial stages of decomposition. The recalcitrant fraction comprises cellulose, lignin and more complex proteins and decomposes more slowly following the action of specialised septate fungi, such as Ascomycetes, Basidiomycetes and Actinomycetes (Sánchez *et al.*, 2008; Martius *et al.*, 2004).

Aguilar *et al.* (2001) found that the decomposition of stems in agroforestry systems such as coffee fit the double exponential model better. Isaac *et al.* (2000) reached the same conclusion in a study on the decomposition and nitrogen release of pruning from Leucaena species.

Table IV-2. Fit of a double exponential model to pruning residue mass (kg ha^{-1}). SD: Standard Deviation. R^2: Coefficient of determination.

Treatment	***L***	**k_1 [days^{-1}]**	**k_2 [days^{-1}]**	**SD**	**R^2**
I	0.347	7.90×10^{-3}	8.23×10^{-4}	489.97	0.99
II	0.200	10.00×10^{-3}	14.22×10^{-4}	902.56	0.98
III	0.300	1.82×10^{-3}	16.46×10^{-4}	1303.30	0.98
IV	0.194	348×10^{-3}	11.90×10^{-4}	3889.40	0.91

IV-3.2. Soil cover

Figure IV-4 depicts the temporal evolution of the cover percentage for the different pruning residue treatments. All treatments recorded a high percentage of cover throughout the decomposition cycle with covers ranging from 80% to 99% being observed in the majority of samples taken.

We can see that throughout the decomposition cycle in both years, none of the pruning residue treatments exhibit coverage rates below 30%, which is considered the minimum threshold at which the soil would be protected from external agents, according to the definition of conservation agriculture indicated by the Conservation Tillage Information Centre (1990). However, Snelder and 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 rapidly increased. In our case, this cover percentage was exceeded in all the treatments and sampling dates. This is important because the benefits of establishing plant covers for soil protection against erosive agents and for improving their water balance are associated with the presence of plant remains which maintain a dense cover on the soil for the longest possible time.

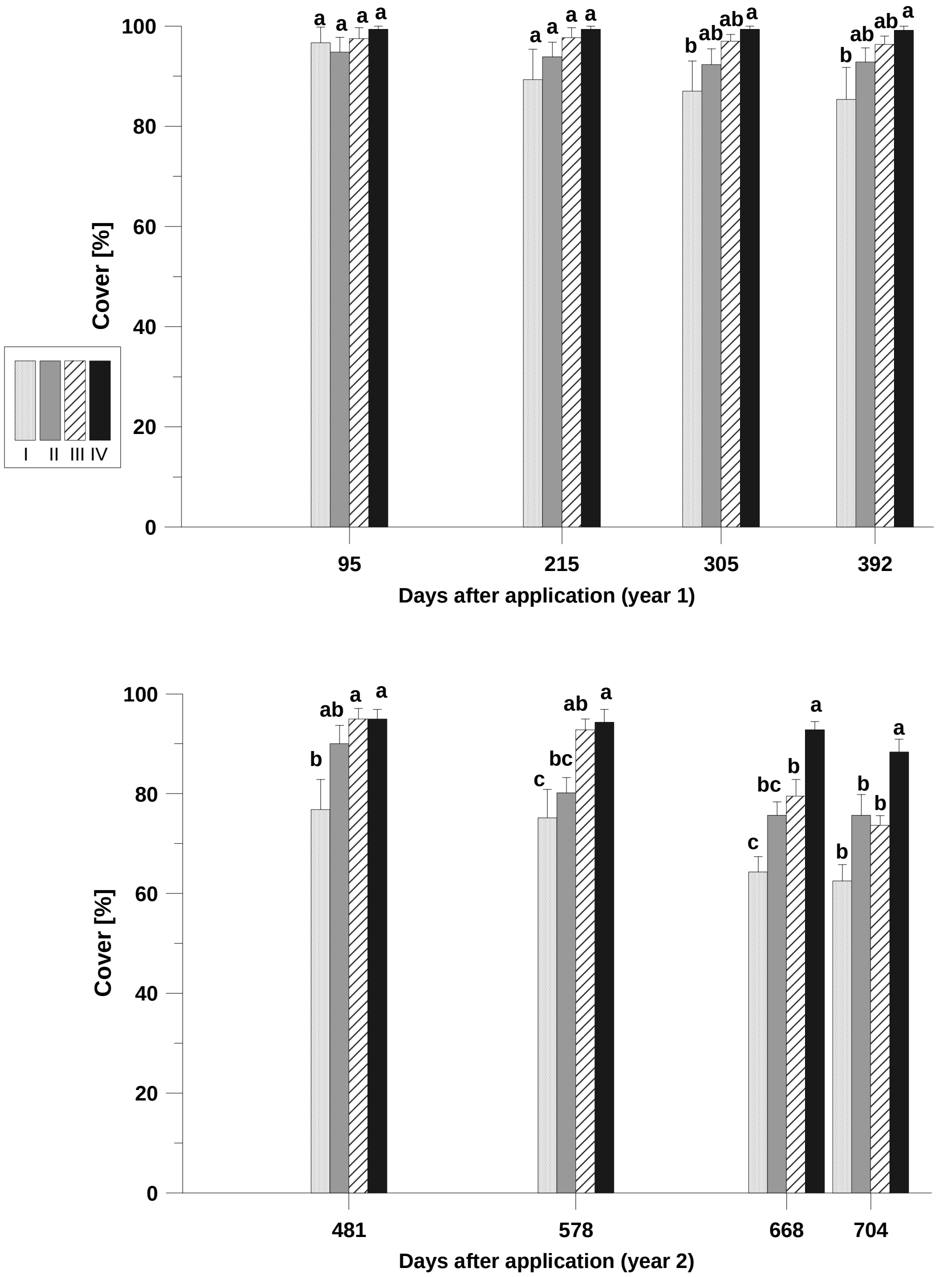


Fig. IV-4. Temporal evolution of the cover percentage for the different sampling dates and treatments considered in the study. The vertical lines represent the standard errors. Different letters on a specific date indicate significant differences compared with Tukey's test p≤0.05.

The percentages of cover in this study contrast with those estimated by Rodríguez-Lizana *et al.* (2007). In their study on the temporal evolution of the cover percentage provided by spontaneous weeds in an ecological olive grove, cover ranged between 35% and 75% for two agricultural years. As can be seen in Figure IV-4, the loss of cover is directly proportional to the amount of residue applied to the soil, except between treatments II and III. In this case, the fact that treatment II has a fraction of thick residues causes it to maintain more cover until the end of the period under study, although there are only significant differences between treatments with treatment IV.

IV-3.3. Spatial-temporal distribution of the residue on the soil

By analysing how stable the cover is over time, we can define the persistence of a behaviour model of each strip with respect to the rest and identify areas with scant or excessive cover.

Figures IV-5 I), II), III) and IV) show the mean covers of the 12 strips or controlled positions. This study is not interested in determining a point with average behaviour, as in Vachaud *et al.* (1985), but rather in preventing accumulations of biomass or cover at certain points of the plot on the one hand, which hinder operations in the grove and condition the decomposition of the residue and the presence of points with scant cover on the other, where there is poor protection against erosion (Zuzel and Pikul, 1993). In the case of treatment I, in which a lower proportion of fine residues was applied, variability was observed, with a minimum mean value of 68% compared to a maximum mean value of 92%. There is less variability in the rest of doses with minimum values of 78%, 86% and 90% and maximum values of 92%, 95% and 100% for treatments II, III and IV, respectively.

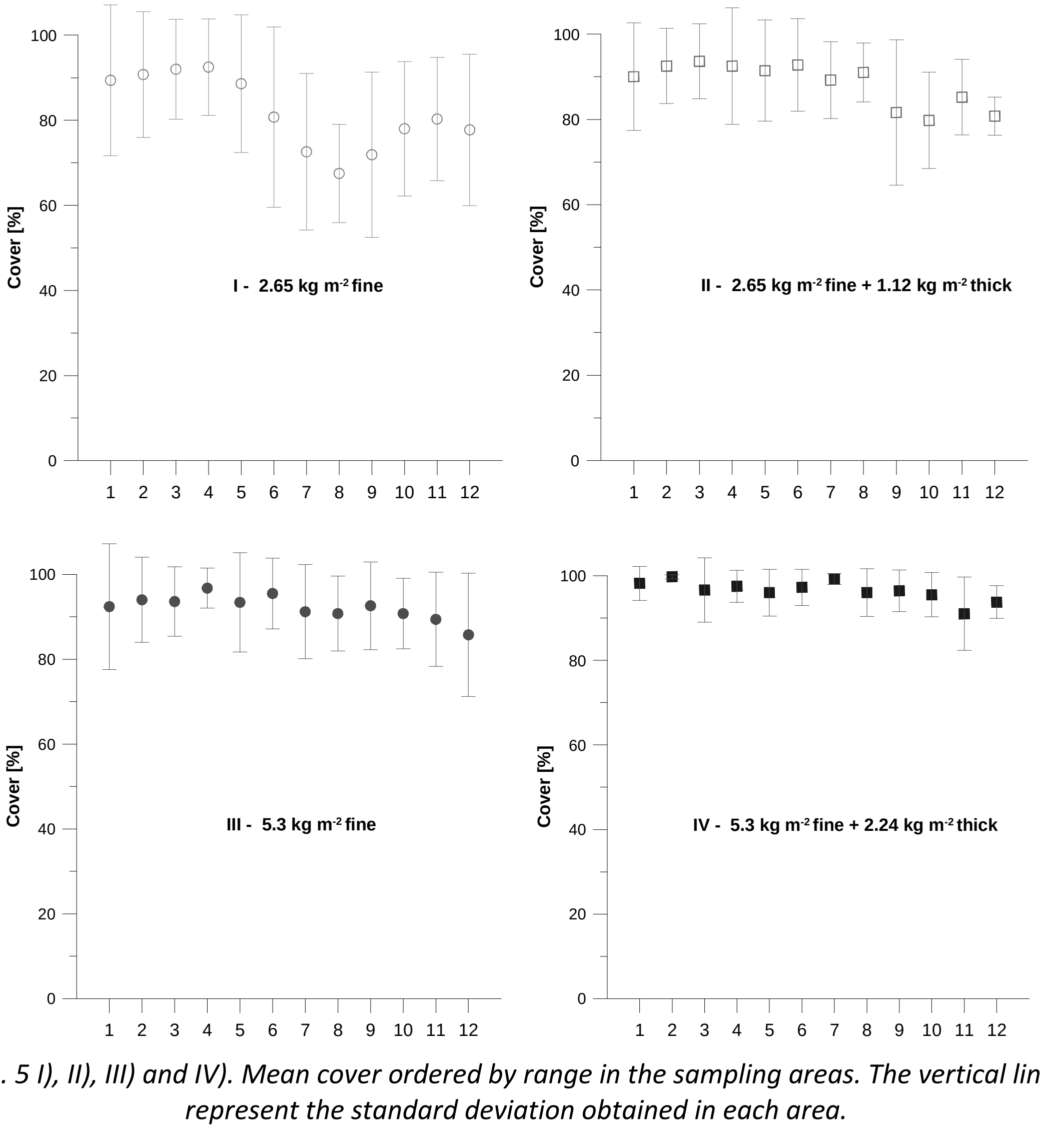


Fig. 5 I), II), III) and IV). Mean cover ordered by range in the sampling areas. The vertical lines represent the standard deviation obtained in each area.

Treatment IV records the greatest temporal stability of cover with respect to the position, which results in a lower standard deviation (Fig. IV-5 IV), whereas the greatest temporal variations per position occur in treatment I (Fig. IV-5 I), due to this matter decaying more easily.

IV-3.4. Carbon release

In addition to protecting the soil, another important characteristic of the residues is that of providing the soil with nutrients and carbon as they decompose.

The dynamics of the carbon release with the decomposition of the residues is similar to the evolution of the biomass. Figure IV-6 shows how the carbon release constant, *k*, is similar for all the treatments and lower than that estimated by Ordóñez *et al.* (2007c) in a study on the decomposition of sunflower stubble (*Heliantus annus*), which was 0.0049 (day^{-1}) and that measured by Boniche *et al.* (2008), which was 0.0064 (day^{-1}) after the decomposition of harvest residues in heart-of-palm plantations (*Bactris gasipaes*).

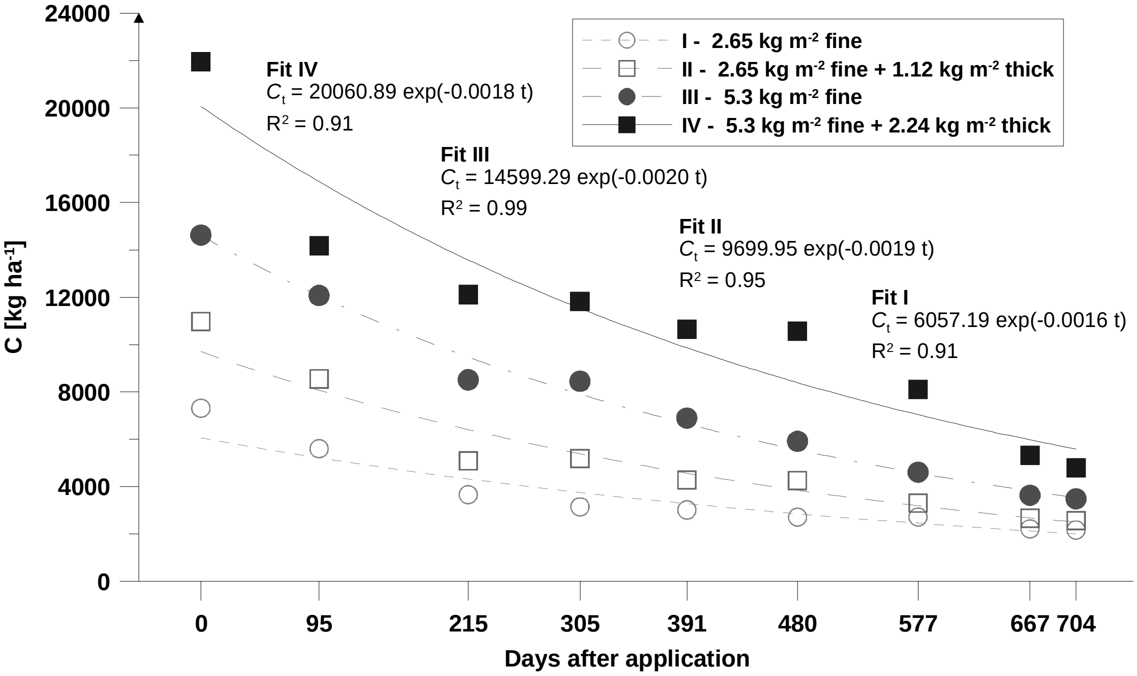


Fig. IV-6. Carbon remaining in different pruning treatments as a function of the time and simulated values. Units are kg of Carbon per ha of cover.

After 704 days, treatment IV had released the largest amount of carbon with a value of 16630 kg ha^{-1}, followed by III with 10989 kg ha^{-1}, II with 8306 kg ha^{-1} and I with 5093 kg ha^{-1}. The difference in the amount of carbon lost is considerable between treatments. In fact, the carbon release rate in the maximum dose was 3.3 times higher than that measured in the treatment with a smaller amount of residues.

The amount of carbon released by the decomposition of the different pruning residue treatments contrasts with that estimated by Ordóñez *et al.* (2010) in different species of crop covers used in the olive grove, such as *Brachypodium distachyon* (1911 kg of C ha^{-1}), *Eruca vesicaria* (1471 kg of C ha^{-1}), *Sinapis alba* (404 kg of C ha^{-1}) and spontaneous weeds (509 kg of C ha^{-1}), for a decomposition period of 172 days. Pruning residue released 3652, 5880, 6109 and 9832 kg of C ha^{-1} according to the treatment for the same decomposition period.

Despite the differences observed, the overall carbon loss percentage with respect to the beginning of the experiment was similar for the different treatments, maintaining a percentage of 30%, 24%, 25% and 24% for doses I, II, III and IV, respectively (Figure IV-7). In the first year of cover establishment, the percentage of carbon released exceeded 50% in all treatments as a result of the decomposition of the residue labile fraction.

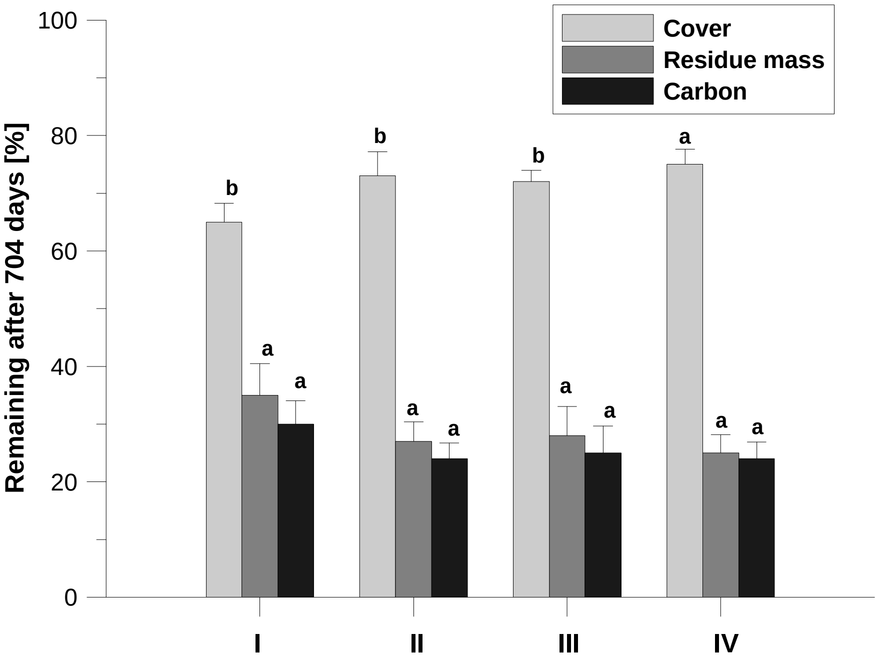


Fig. IV-7. Percentage of cover, residue mass and carbon remaining after 704 days of decomposition for the different treatments considered in the study. The vertical lines represent the standard errors. Different letters in a specific type of bar indicate significant differences between treatments compared with Tukey´s test p≤0.05.

IV-3.5 Soil carbon content

The overall fertility of agricultural soil has always been related to its content in organic matter. Maintaining adequate levels of organic matter in the soil is of great agronomic importance as it intervenes in all the processes connected to structure dynamics, to plant growth and the macro and microbial life sustaining it (Bravo *et al.*, 2006). Organic matter has lately been receiving special attention due to its potential for sequestering carbon, thus diminishing atmospheric CO_2 emissions (Farina *et al.*, 2011).

We have assessed the effect of applying different treatments of pruning residues and spontaneous weed cover on the variation in the concentration of organic matter on the surface (0-5 cm) and to a depth of 20 cm (Table IV-3). In comparison to the beginning of the experiment, the most favourable situation was displayed by treatment IV, which increased SOM content on the surface by approximately 5 Mg ha^{-1} more than treatments I, II and III and 11 Mg ha^{-1} more than the control, which is the treatment that records significant differences in regard to the rest of treatments.

Consider the total amount of soil sampled, treatment III registers a significantly higher increase in SOM concentration than the rest of treatments, with a score that was approximately 10 Mg ha^{-1} in relation to that estimated in the case of the other treatments of pruning residues and 24 Mg ha^{-1} in comparison to the control (Table IV-3).

Nieto *et al.* (2010) observed how the SOC in olive grove soil increased from 27.1 Mg ha^{-1} in the first 10 cm of soil to 113.6 Mg ha^{-1} after applying pruning residues as plant cover for a period of five years.

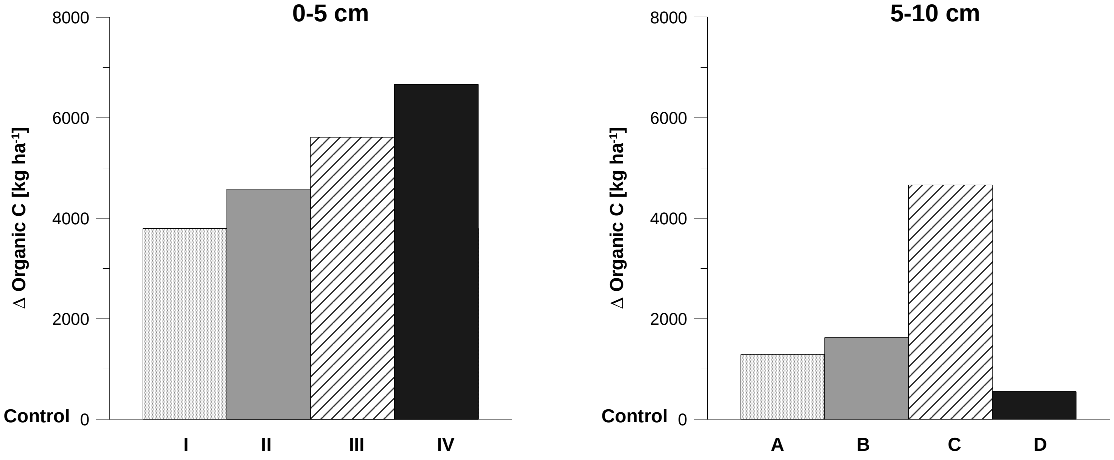
Table IV-3. Increase in SOM content in regard to the initial situation and the control treatment at depths of 0-5 cm and 0-20 cm. Different letters indicate significant differences compared with Tukey's test p≤0.05.

Depth [cm]	Treat	$\Delta_{beginning}$ SOM [%]	$\Delta_{control}$ SOM [%]	$\Delta_{beginning}$ SOM [Mg ha^{-1}]	$\Delta_{control}$ SOM [Mg ha^{-1}]
0-5	I	2.28 ab	0.86 a	16.98	6.46
	II	2.20 ab	1.04 a	16.37	7.78
	III	2.25 ab	1.28 a	16.70	9.53
	IV	2.90 a	1.52 a	21.53	11.32
	Control	1.42 b		10.52	
0-20	I	0.33 ab	0.43 a	15.71	12.73
	II	0.29 ab	0.46 a	16.51	13.53
	III	0.63 a	0.84 a	27.97	24.99
	IV	0.36 ab	0.47 a	16.96	13.98
	Control	0.10 b		2.98	

After 704 days of decomposition y considering the entire soil profile sampled, the organic carbon percentage increased with respect to the moment at which the pruning residues were applied to the soil by 46% for treatment I, 48% for II, 81% for III, 49% for IV and 9% for the control treatment.

As was the case for the different pruning residue treatments, the level of organic carbon in the control treatment also increases as a consequence of the decomposition of the spontaneous weeds and flowers, leaves and fruit that fall on the ground and accumulate in the area.

In order to be able to estimate the real accumulation of organic carbon provided by the pruning residue cover, the value of this parameter in the control was subtracted from that estimated for the rest of the treatments. The result of this calculation is represented in Fig. IV-8 and different depths have been considered to assess the effect of pruning residues in deeper layers.



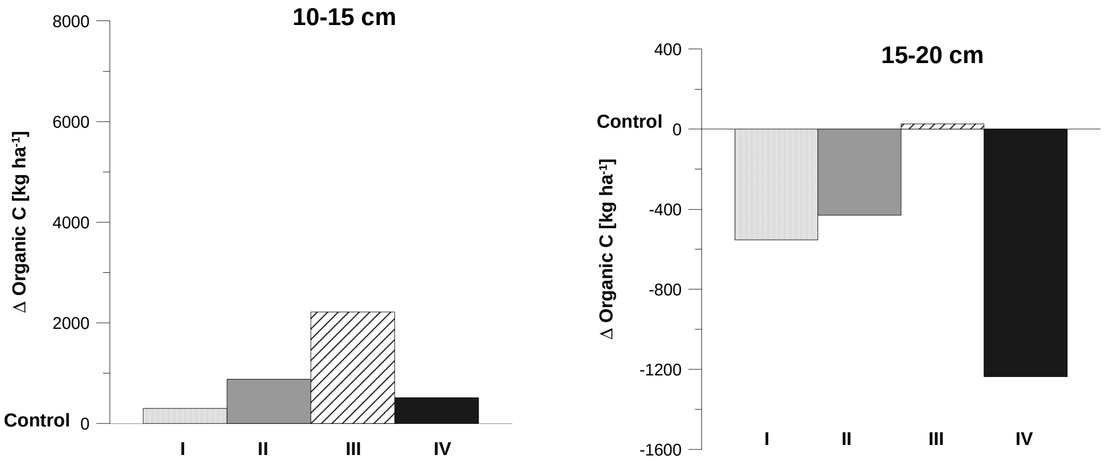


Fig. IV-8. Increase in organic carbon fixed in the soils following the different pruning residue treatments with respect to the control for the depths sampled. Units are kg of Soil Organic Carbon per ha of cover.

As seen in the figure, the application of pruning remains improved the content of organic carbon down to a depth of 15 cm, treatment IV being the most favourable on the surface and treatments II and III at depth. These results coincide with those obtained by Ordóñez *et al.* (2007b) in a six-year study in which pruning residues were applied to the soil of an untilled olive grove maintained with bare soil. In that case, the authors noted an increase in organic matter content in covered soils in the first 10 cm of the profile.

The non alteration of the soil, leaving cover residues on the surface for 704 days, determined the following amounts of organic carbon accumulated in the first 5 cm of the soil (where the greatest differences are observed): 3.8 Mg ha^{-1}, 4.6 Mg ha^{-1}, 5.6 Mg ha^{-1} and 6.7 Mg ha^{-1} for treatments I, II, III and IV, respectively, with respect to the content of this parameter in the control treatment. In this sense, the amount of carbon sequestered in the soils was 1.7 times higher than that measured in the treatment with a lesser amount of residues.

Nieto *et al.* (2010) assessed the increase in SOC content in two olive groves where pruning residues were applied as cover, observing an increase of 1.88 and 2.33 Mg ha^{-1} in one year. Romanyà *et al.* (2000) registered similar results for a vineyard in the Mediterranean area, with an annual carbon input of 1.4 Mg C ha^{-1} yr^{-1}.

The values observed were higher than those estimated by Castro *et al.* (2008) in olive grove soil in which the plant cover was maintained for 28 years, but similar to the ones estimated by Márquez *et al.* (2008) in an olive grove with a cover for 4 years. In both cases, the cover was spontaneous weeds. These values coincide with Hernández *et al.* (2005), although the residue mass at beginning was smaller and the experiment lasted for 5 years.

Several studies have suggested that the Soil Organic Carbon content increases rapidly during the first ten years after the change from traditional soil management systems to protect soil systems. After this period, the increases slow until near zero growth in the OM content is reached, indicating soil equilibrium (Puget and Lal, 2005).

IV-4. CONCLUSIONS

Pursuant to current legislation, the elimination of pruning remains in olive groves in the south of Spain must be performed in accordance with the decree that regulates the prevention and combating of forest fires. This decree establishes restrictions in terms of how and when such remains can be burned, which together with the large amount of labour this practice entails, has led olive growers to seek alternative solutions for eliminating these remains in such a way as to take advantage of their ability to protect and enhance soil fertility.

Any of the treatments considered in the study could be used to protect the soil, as all of them easily surpassed the threshold of 30%, beyond which soil is considered to be protected from external agents. The treatment with the largest amount of residues (IV) recorded less spatial variability and greater temporal cover stability, although it did lose 2, 2.8 and 3.5 times more mass in the decomposition period than treatments III, II and I, respectively.

The largest amount of carbon (over 50%) is released in the first 12 months of decomposition as a consequence of the attack by microorganisms of the most labile organic C fractions of pruning residues. The recalcitrant fractions of organic C are the most difficult to decompose and, hence, the organic carbon release slows down due to the evolution of the residues in the second year. The low carbon release constant measured in the different treatments confirms that it is more difficult for these types of residues to decompose.

The favourable results observed in terms of how much soil organic carbon increased after applying pruning remains confirm an improvement in soil fertility in regard to that recorded by spontaneous weeds cover, which is the most widely used in organic olive groves. Although treatment IV registers a larger increase in carbon on the surface, treatment III recorded the best results in carbon sequestration when considering the entire volume of soil with respect to the control.

In view of the results obtained, we believe it is more recommendable to apply fine residue treatments that, due to having a greater proportion of labile remains, decompose more easily, thereby allowing olive growers to apply the next pruning remains to the soil. Furthermore, such treatments improved the levels of organic matter in a larger volume of soil. The thick pruning residues could be used as energy biomass.

IV-ACKNOWLEDGEMENTS

To the field and laboratory personnel of the physics and chemistry of soils team at the IFAPA Centre, Alameda del Obispo, for their collaboration in the trials, the Department of Innovation, Science and Enterprises of the Autonomous Government of Andalusia for their financial support through the Project of Excellence RNM 03-205 and to the project RTA2010-00026-C02-01 funded by INIA in the framework of the “National Subprogramme of Agricultural Resources and Technologies with the Autonomous Communities” under the National Plan for Research, Development and Technological Innovation (I+D+I) and co-financed by the European Union via FEDER funds.

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Chapter V.

Macronutrients released during the decomposition of pruning residues used as plant cover and their effect on soil fertility

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Ordóñez-Fernández, R., Repullo-Ruibérriz de Torres, M.A., Román-Vázquez, J., González-Fernández, P., Carbonell-Bojollo, R., 2014. The Journal of Agricultural Science, in press, doi: 10.1017/S0021859614000458.

Chapter V. Macronutrients released during the decomposition of pruning residues used as plant cover and their effect on soil fertility

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(Accepted in The Journal of Agricultural Science 2014, doi: 10.1017/S0021859614000458.)

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V-SUMMARY

The arrival on the market of various types of mulchers and chippers has boosted the use of pruning residues as plant cover among olive growers. In order to increase knowledge regarding the decomposition of these types of residues and their effect on soil fertility, an experiment was performed using different doses and sizes of pruning residues applied on the areas between the lines of olive trees in an organic olive grove.

Experiments were conducted over a period of two growing seasons (2009/10 and 2010/11). Treatments consisted of fine (≤ 8 cm in diameter) and thick (> 8 cm in diameter) pruning residues in the amounts indicated, I = 2.65 kg/m^2 fine; II = 2.65 kg/m^2 fine + 1.12 kg/m^2 thick; III = 5.30 kg/m^2 fine; IV = 5.30 kg/m^2 fine + 2.24 kg/m^2 thick; and a control without residues
As regards the loss of biomass and nutrients during the decomposition of residues, two phases were observed. First, soluble compounds were degraded during a rapid initial phase, while in a second and slower phase, lignocellulosic compounds were decomposed. As a result, the pattern over time of nitrogen (N), phosphorus (P) and potassium (K) release fitted a double exponential model better, regardless of the treatment considered, registering in most cases determination coefficients close to one.

The favourable results observed in terms of augmentation in N, P and K soil content following the application of pruning residues confirmed a greater improvement in soil fertility than the soil covered by spontaneous weeds, which is the option most frequently adopted by organic olive growers. The initial amount of pruning residues has influenced the increment of soil nutrients. Considering the entirety of the soil profile (0–40 cm) and the content of these elements in the soil, treatment III, which contained the largest amount of fine residues, was the most efficient in terms of improving soil fertility, recording increases in the concentration of N, P and K of 1805.4 kg/ha, 53.1 kg/ha and 598.7 kg/ha respectively. The most unfavourable results were recorded by treatment I, with increases of 480.9 kg/ha in the case of N and a decrease in P content in regard to the control sample. Treatment II increased K (recording 215.2 kg/ha) which was the least in comparison to the control sample.

Keywords: olive tree; pruning residues; residue decomposition; N, P and K release; soil N, P and K.

V-1. INTRODUCTION

Organic olive groves account for *c*. 0.19 of total organic surface area in Spain. In Andalusia, this crop represents 0.38 of the surface area devoted to agriculture and its presence on the region's farmland has increased over time, from 9083 ha in 1996 to nearly 47000 ha registered in 2010 (CAP 2011). This type of olive-growing system constitutes an economic opportunity for certain rural areas that, generally speaking, are not very productive and supplies a differentiated quality of product that is subject to ever-increasing demand in Europe (El-Hage Scialabba & Hattam 2002). Support from the European Union has contributed towards the growth of this system by including this farming activity in the group of agricultural production methods that favour the fulfilment of agro-environmental goals (Regulation 2078/1992, European Comission 1992).

Organic olive groves in Andalusia are generally located in mountain regions with steep slopes and acidic and shallow soil with little organic matter**.** Two of the most significant problems in organic olive-growing systems are the high rates of erosion and the fact that the olive growers cannot use synthetic fertilizers. As a result, maintaining the natural fertility of the soil has become a key factor (Rembialkowska 2004; Rosati & Aumaitre 2004).

In this sense, implementing plant cover as part of a sustainable system may help a great deal, as this raises the levels of organic matter and, therefore, the mineral nitrogen (N) available for olive growth (Wells *et al*. 2000), together with other nutrients. Furthermore, according to Korsaeth & Eltun (2000), in order for a farming system to be sustainable, it must not only have a suitable level of nitrogen in the soil, but also minimize the losses through run-offs and leaching, underlining the fact that crop rotations handled organically struggle to maintain their output if the soil is continually tilled.

One of the most inert plant covers is pruning residues, which have several benefits for the soil they are applied to. Pruning residues decompose and humify slowly, due to their high proportion of cellulose and lignin, a medium-low content of moisture and a high carbon (C)/N ratio, which ensures soil protection over time (Ordóñez *et al*. 2007). The application of pruning residues to the areas between the lines of perennial crops has been backed by the Government and recommended by specialists, mainly due to soil protection and the extra organic matter this practice produces.

In order to develop this type of system, there must be awareness of the quality and evolution of the residues generated by an agricultural system to be able to establish strategies for handling them. The decomposition of plant residues is a vital process in ecosystems, as it influences the supply of organic matter in the soil and the release of nutrients for plant uptake (Prescott 2005).

Many studies of decomposition analyse the relationship between the chemical characteristics of plant residues and the loss of weight from the matter decomposing, while fewer studies assess the effect of interactions between the residue quality and speed of decomposition on the underlying soil (Sariyildiz & Anderson 2003; Semmartin 2006).

Moreover, the chemical composition of the residues, the decomposition rate and the subsequent release of nutrients is regulated by the weather, the biodiversity of microbial communities, the physical and chemical degradation, the quantity of plant residues applied and the application frequency (Carrera *et al*. 2005; Austin & Vivanco 2006; Gallo *et al*. 2006).

In the case of most crops, growers reject the idea of quantifying the nutrients that are produced by residual biomass decomposition and as a result overuse inputs, which has repercussions for the environmental and economic sustainability of the system. However, some residues provide permanent biomass that gradually releases nutrients as they decompose, with a subsequent effect on soil fertility. Ordóñez *et al*. (2001) assessed the impact of constantly maintaining olive tree pruning residues as plant cover for a period of 6 months, observing significant improvements in the characteristics of the soil.

Few papers have been found to specify the effects of applying olive tree pruning residues on the properties of soil and fewer still have provided quantitative data on the amount of such organic residues, generated by the olive grove itself, that is required to reap the benefits of improving soil fertility.

The goal of the current research was to assess the decomposition dynamics of various doses and sizes of plant residues by measuring the developments that take place in their composition and their capacity to release N, phosphorus (P) and potassium (K) for the soil of an organic olive grove.

V-2. MATERIALS AND METHODS

V-2.1. Field trials and experiment design

The current study was performed at the IFAPA centre 'Alameda del Obispo' in Córdoba, Spain (37º 51′ N and 4º 47′ W; 117 m a.s.l.). The organic olive orchard has 'picual' olive trees 40 years old and a plantation frame of 8 × 8 m.

The climate in the area where the experiment was performed is typically Mediterranean, characterized by xeric humidity according to the standards established by Soil Taxonomy (Soil Survey Staff 1998). This climate entails a cold and wet period in the autumn and winter months, which account for 0.80 of rainfall and a very warm and dry period in spring and summer. The temperature regime is thermic. The soil is a Calcixerept Inceptisol, according to Soil Survey Staff (1999). Table 1 shows soil physicochemical characteristics of the experimental area. The experiment was conducted over a period of two growing seasons (2009/10 and 2010/11), which corresponds to the time between two prunings.

Table V-1. Physicochemical characteristics of olive grove soil used in the trial.

Depth	**pH (H_2O)**	**pH (Cl_2Ca)**	**$CO_3^=$**	**CEC**	**sand**	**silt**	**clay**	**Textural Class**	**OM**
cm			*g/kg*	*mol$_c$/kg*	*%*	*%*	*%*		*%*
0-20	8.6	7.8	164	0.20	41.6	40.6	17.8	Loam	1.9
20-40	8.6	7.8	204	0.19	44.6	37.6	17.9	Loam	1.3
40-60	8.8	7.9	209	0.17	44.9	37.5	17.7	Loam	1.0

CEC, Cation Exchange Capacity; OM, Organic Matter.

In order to perform the trial, different olive trees on the farm were pruned and the residues obtained per tree were weighed, differentiating the fine wood (light pruning from the cleaning of the orchard, with a diameter equal to or below 8 cm), from the thick wood (renewal pruning greater than 8 cm in diameter), and applied to the soil.

In order to include the various chopping options currently available to farmers, two types of chopping were distinguished depending on the size of the residues, namely field treatments with self-fed and hand-fed chopping machines. Therefore, two treatments were adopted, namely treatment I (fine residues) and treatment II (fine and thick residues).

During pruning, the residues from two rows are usually accumulated on an inter-row. This operation let to occupy only half inter-rows, reducing the work of chopping and scattering machinery. For that reason, another two treatments were adopted: treatment III (fine residues) and IV (fine and thick residues) having double the residues of treatments I and II.

The doses per unit of surface area were adopted in accordance with the average pruning output of 10 olive trees and the distance between olive trees considering a residue application strip (cover strip) width of 2 m: 42.4 (S.E. = 4.4) kg fine pruning per tree / (8 m between olive tree × 2 m of cover strip width) = 2.65 kg fine pruning/m^2; 17.9 (S.E. = 2.4) kg thick pruning per tree / (8 m between olive × 2 m of cover strip width) = 1.12 kg thick pruning/m^2.

Table V-2 shows the different doses of residues used and nutrients added in the study and a control treatment of spontaneous weeds where no residues were applied.

Table V-2. Doses of olive pruning residues applied to the soil in kg/m^2 (wet weight) and nutrient content in the pruning in kg/ha (dry matter).

Treatments	**Fine size** *kg/m^2*	**Thick size** *kg/m^2*	**Total** *kg/m^2*	**N** *kg/ha*	**P** *kg/ha*	**K** *kg/ha*
I	2.65	0	2.65	132.59	28.73	80.45
II	2.65	1.12	3.77	160.53	34.90	100.87
III	5.30	0	5.30	265.17	57.46	160.90
IV	5.30	2.24	7.54	321.06	69.79	201.75
Control	0	0	0	0	0	0

Fine size: ≤ 8 cm in diameter; Thick size: > 8 cm in diameter

Control sub-plots were characterized by species and biomass of spontaneous weeds. The control treatment had 1848 kg/ha of spontaneous weeds at the beginning of the experiment. The main annual species of weeds were *Bromus madritensis, Bromus hodeaceus, Avena barbata* and *Hordeum leporinum.* In spring and summer*, Medicago sativa, Convolvulus arvensis, Cyperus rotundus* and *Crepis vesicaria* had also grown, adding *c*. 400 kg/ha of weed biomass.

The experimental design was a randomized complete block with six replications. The experimental unit was a sub-plot of 28 m^2; it consisted of the distance between three trees, leaving 2 m between sub-plots (14 m), per cover width of 2 m.

V-2.2. Sampling

Because of the high C/N ratio of pruning residues, which limited decomposition, sampling was performed on a quarterly basis. The residue mass was estimated from the prunings collected in a 0.25 m^2 metal frame from the soil, which served to delimit the sampling area and was placed at all the points selected. The residue collected was sent to the laboratory, where it was washed with distilled water to prevent contamination in the subsequent analysis and placed in an oven at 65ºC until it reached a constant weight and it was possible to estimate the amount of dry matter.

At the end of the second year, soil sampling at depths of 5, 10, 20 and 40 cm was performed to assess the effect of applying the pruning residues. The soil samples were taken with an Edelman auger. A cylinder of known volume was used to measure bulk density. Soil samples were air-dried and sieved through a 2 mm mesh sieve for subsequent analysis.

V-2.3. Analysis of samples

Residue and soil samples were analysed for total nitrogen content using a LECO (TRUSPEC, CNS; St. Joseph, MI, USA) elemental analyser. Total P content in residues was determined by colorimetry and total K by atomic absorption spectrophotometry, both after converting the sample into ash and dissolving it in 100 ml HCl 0.1N. Available P in soil was measured by colorimetry and exchangeable K by atomic absorption spectrophotometry after extracting with $NaHCO_3$ 0.5M and CH_3COONH_4, respectively (Sparks *et al*. 1996).

V-2.4. Nitrogen, Phosphorous and Potassium release

The release rate of N, P and K from the different pruning residue treatments was estimated. It was calculated as the difference between the content of this element in the residues when they were applied to the soil, and a comparison sample of a specific date, according to the Eq. [1]:

$$\text{Released Nutrient}_t = Y_0 - Y_t \qquad [1]$$

where Y_t is the amount of nutrient remaining in the residue at time t (kg/ha) and Y_0 the amount of this nutrient remaining in residues when these were applied to the soil (kg/ha).

In order to describe the reduction of the remaining amount of considered nutrient (N, P, K) in residue, two models were fitted by means of non-linear regression. The first was the simple negative exponential model (Olson 1963), which is described by Eq. [2]:

$$Y_t = Y_0 \exp(-k\,t) + \varepsilon \qquad [2]$$

where Y_t is the amount of nutrient remaining at time t, Y_0 is the estimated nutrient pool at t = 0, k (1/day) is the nutrient release rate constant, t is time (in days after application) and ε is the random error.

The second was a double exponential decay model (Bunnell & Tait 1974) [eq. 3], which takes into account the fractions of easy and difficult decomposition. The corresponding equation is as follows:

$$Y_t = Y_0\, L\, exp\left(-k_1\, t\right) + Y_0\left(1-L\right) exp\left(-k_2\, t\right) \qquad [3]$$

where Y_t (kg/ha) is the remaining amount of the considered element (N, P, K) at time t; Y_0 (kg/ha) the quantity of that element remaining at the beginning (t = 0 days); L is the Labile fraction and 1-L the difficult decomposition fraction; k_1 and k_2 (1/days) are the decay constants of the labile and recalcitrant fraction, respectively and t (days) is the time considered. In order to select the models, the determination coefficient (R^2) was used as an indicator of goodness of fit.

V-2.5. Soil N, P and K

The amount of N, P and K in soil was calculated according to Eq. [4]:

$$X\left(\frac{kg}{ha}\right)=\%X\left(\frac{kg_X}{100kg_{soil}}\right)\times\rho_b\left(\frac{kg_{soil}}{m^3}\right)\times D(m)\times 10^4\left(\frac{m^2}{ha}\right) \quad [4]$$

where *X* is the nutrient, ρ_b is the bulk density of soil and *D* the depth of soil we refer to.

For each treatment (*T*) the content of N, P and K accumulated at a given depth (*D*) was calculated using Eqn (5):

$$X_{D,T}\left(\frac{kg}{ha}\right)=\sum_{1}^{n} X_i\left(\frac{kg}{ha}\right) \quad [5]$$

where *i* is the number of depth intervals sampled. Three intervals at depth of 0-20 cm (0-5, 5-10 and 10-20 cm) and one interval at depth of 20-40 cm.

The increase in N, P and K content in soil for the different treatments with respect to the control was obtained according to Eq. [6]:

$$\Delta X_{D,T}\left(\frac{kg}{ha}\right)=X_{D,T}\left(\frac{kg}{ha}\right)-X_{D,Control}\left(\frac{kg}{ha}\right) \quad [6]$$

and the percentage increase over the control was calculated as follows:

$$\frac{\Delta X_{D,T}\left(\frac{kg}{ha}\right)}{X_{D,Control}\left(\frac{kg}{ha}\right)}\times 100 \quad [7]$$

V-2.6. Data analysis

Weather in the local area was monitored during the 2-year study, assessing rainfall and maximum and minimum daily temperature data. The data were taken from a weather station located 500 m from the experimental plot, which belongs to the network of agricultural weather stations (RIA) of the Andalusia Regional Ministry of Agriculture, Fisheries and the Environment (Spain).

The residual amounts of nutrients analysed at each moment in time were calculated using the product of the dry matter of the residues by the concentration of the element on the day of sampling. The amount of N, P and K remaining (kg/ha) at each sampling were regressed in time using the non-linear regression model procedure of SPSS 15.0. The double exponential model was fitted to the data using the non-linear regression model provided by the Statistix 9.0 program.

In order to determine the association between the behaviour of the dry matter of the residues and the nutrients analysed, the Pearson linear correlation coefficients between the variable biomass (kg/ha), N, P and K content (kg/ha) and C/N, N/P, N/K and P/K were calculated. This relationship was measured for all samplings. Statistix 9.0 software program was used for statistical analysis.

The ANOVA statistical test was employed to nutrients in residues and soil and with a comparison of means (Tukey's test $P \leq 0.05$).

V-3. RESULTS

V-3.1. Dry Matter evolution

The Mediterranean climate in the south of Spain, with long periods of drought and irregular rainfall distribution, affects both the quantity and evolution of the residues left on the soil surface.

Table V-3 shows how the pruning residue mass in each of the pruning residue treatments has evolved over time every year. A detailed study of decomposition of pruning residues is shown in Repullo *et al.* (2012).

As can be appreciated, the standard error of the data decreases as the days of decomposition elapse, being bigger in year 2 than in year 1, except for treatment I. However, coefficient of variation increased such as the decomposition proceeded.

Table V-3. Anual evolution of average of remaining pruning residue mass (dry matter), Standard Error (SE), coefficient of variation (CV), decomposition days and proportion of decomposed residue from the beginning of experiment for the different treatments used.

Treatment	Year	Decompositions days	Residue mass [kg/ha]	SE [kg/ha]	CV	Decomposed residue
I	1	392	7746.53	696.56	0.220	0.49
	2	704	5420.53	853.03	0.386	0.85
II	1	392	11293.87	1452.88	0.315	0.48
	2	704	6404.16	806.16	0.282	0.79
III	1	392	17415.20	1788.65	0.205	0.56
	2	704	8709.76	1584.63	0.407	0.72
IV	1	392	27201.47	2031.08	0.183	0.57
	2	704	11960.53	1489.67	0.305	0.69

V-3.2. N, P, K release

Apart from protection, the residues also provided the soil with nutrients. However, this property depends on the quantity and composition of the residue mass and how easily it decomposes.

As regards the three nutrients considered, nitrogen was present in the greatest proportion in pruning residues, recording a percentage of 760 g/kg, compared to 170 g/kg and 470 g/kg in the case of phosphorous and potassium, respectively.

Table V-4 summarizes the amounts of N, P and K released through residue decomposition in each of the treatments considered in the study. As regards N, the release rate for treatment IV was 2.3, 2.0 and 1.1 times greater than in the case of Treatments I, II and III, respectively at the end of second year. Treatments I and III, which only involved fine pruning residues, released a greater proportion of initial N: 0.65 and 0.67, respectively.

Table V-4. Released N, P and K in kg/ha and proportion remaining, from the beginning to the end of first and second year. Standard Error is indicated in parenthesis.

Treatment	Year	Released N (kg/ha)	N*	Released P (kg/ha)	P*	Released K (kg/ha)	K*
I	1	63.9	0.52	15.5	0.46	62.6	0.22
		(3.8)	(0.029)	(1.5)	(0.052)	(2.6)	(0.033)
	2	86.7	0.35	22.5	0.22	75.7	0.06
		(7.3)	(0.055)	(0.9)	(0.032)	(0.5)	(0.006)
II	1	71.2	0.56	17.0	0.51	76.1	0.25
		(17.2)	(0.061)	(2.9)	(0.082)	(4.8)	(0.048)
	2	97.9	0.39	28.2	0.20	95.3	0.06
		(13.5)	(0.084)	(1.0)	(0.008)	(0.9)	(0.009)
III	1	77.4	0.71	35.1	0.39	130.2	0.19
		(40.6)	(0.153)	(4.2)	(0.074)	(4.1)	(0.026)
	2	177.6	0.33	46.9	0.19	151.9	0.06
		(26.3)	(0.099)	(2.6)	(0.045)	(2.0)	(0.012)
IV	1	87.9	0.73	38.8	0.44	153.1	0.24
		(32.4)	(0.186)	(3.6)	(0.051)	(4.2)	(0.021)
	2	200.0	0.38	57.1	0.18	192.0	0.05
		(12.8)	(0.040)	(1.2)	(0.018)	(1.4)	(0.007)

* Proportion of nutrient remaining in pruning residue

The amount of P released during the decomposition of residues displayed a similar trend to that described previously. The proportion of P released in regard to the initial concentration was related to the amount of residues applied to the soil, registering losses of 0.78 in treatment I and 0.82 in treatment IV.

As in the previous cases, the more pruning residues applied, the greater the amount of K released, the largest quantity being recorded by treatment IV, which was 2.5, 2 and 1.3 times greater than in the case of treatments I, II and III, respectively. The proportion of K remaining in the residue was the lowest of all the elements and similar for all the treatments considered (Table V-4).

As regards the quantity of total nutrients released through the decomposition of residues in all treatments, the sequence was as follows: N>K>P (Table V-4). However, the proportion of nutrient released by the residue mass in regard to the initial content followed the sequence K>P>N.

V-3.3. N, P, K evolution and models

Regardless of the element considered, the trend over time of the concentration of the nutrient remaining in the residue mass was similar for the various pruning residue treatments (Figs V-1, 2 and 3). More nutrients were released during the sampling dates: this process slowed down in the second year of study.

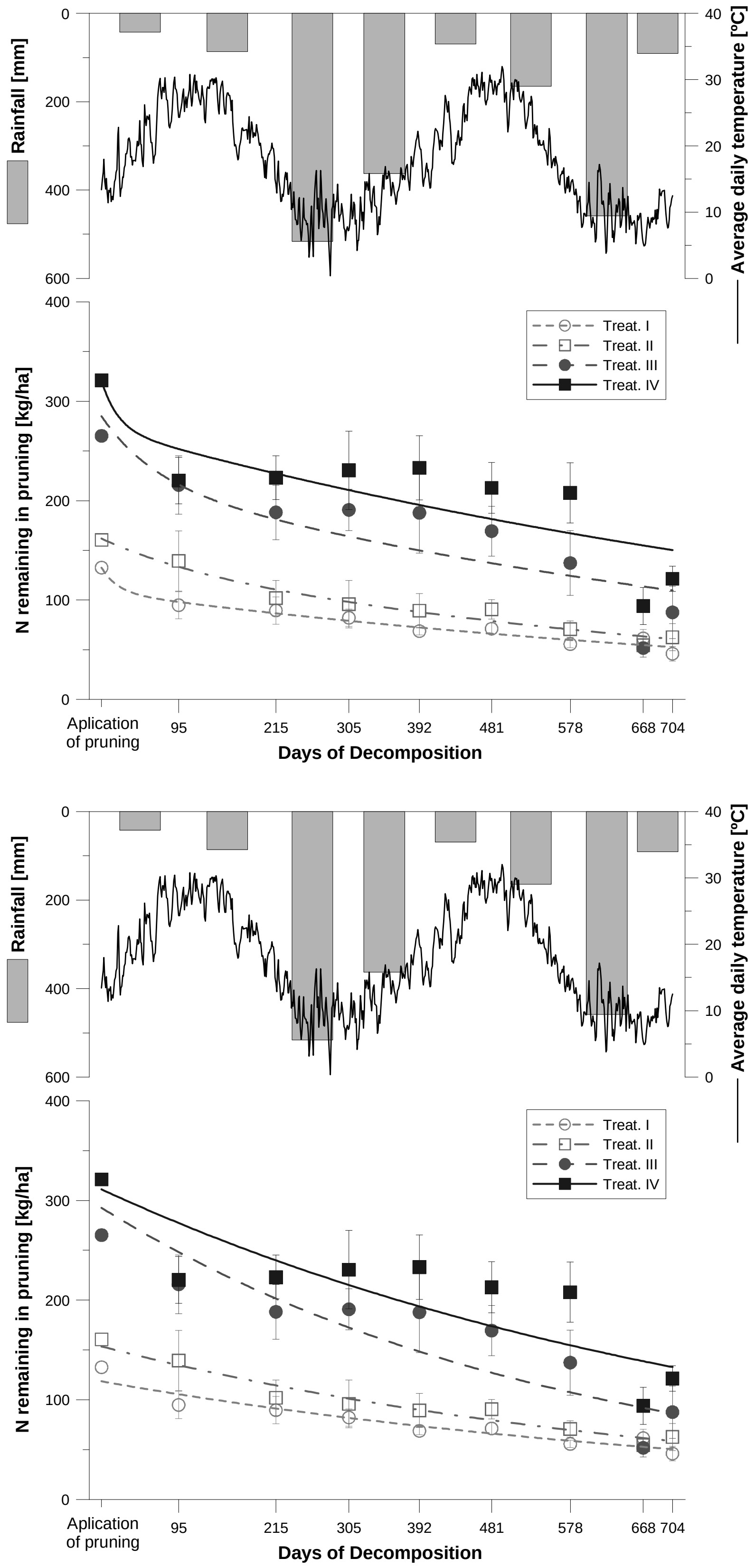

Fig. V-1. Temporal evolution of rainfall, air temperature and kg of N in residue mass per ha of cover in the different pruning residue treatments considered in the study. A double exponential model (above) and a single exponential model (below) have been represented. Vertical lines represent the Standard Error.

As regards N, Fig. V-1 reveals two groups that registered the same pattern. The first group includes treatments III and IV, which had a larger quantity of pruning residues and which also recorded the highest values of N on all sampling dates. The proportion of nutrients released during the first year of the experiment represented 0.43 and 0.22 of the total, respectively. The second group encompasses treatments I and II. In this case, N was released more quickly at the beginning of the experiment due to the mineralization of the residue mass. In fact, a proportion of 0.74 and 0.73 of the total were released in the first year. Treatments III and IV recorded the greatest data dispersion obtained by sampling date and the highest values for the standard error.

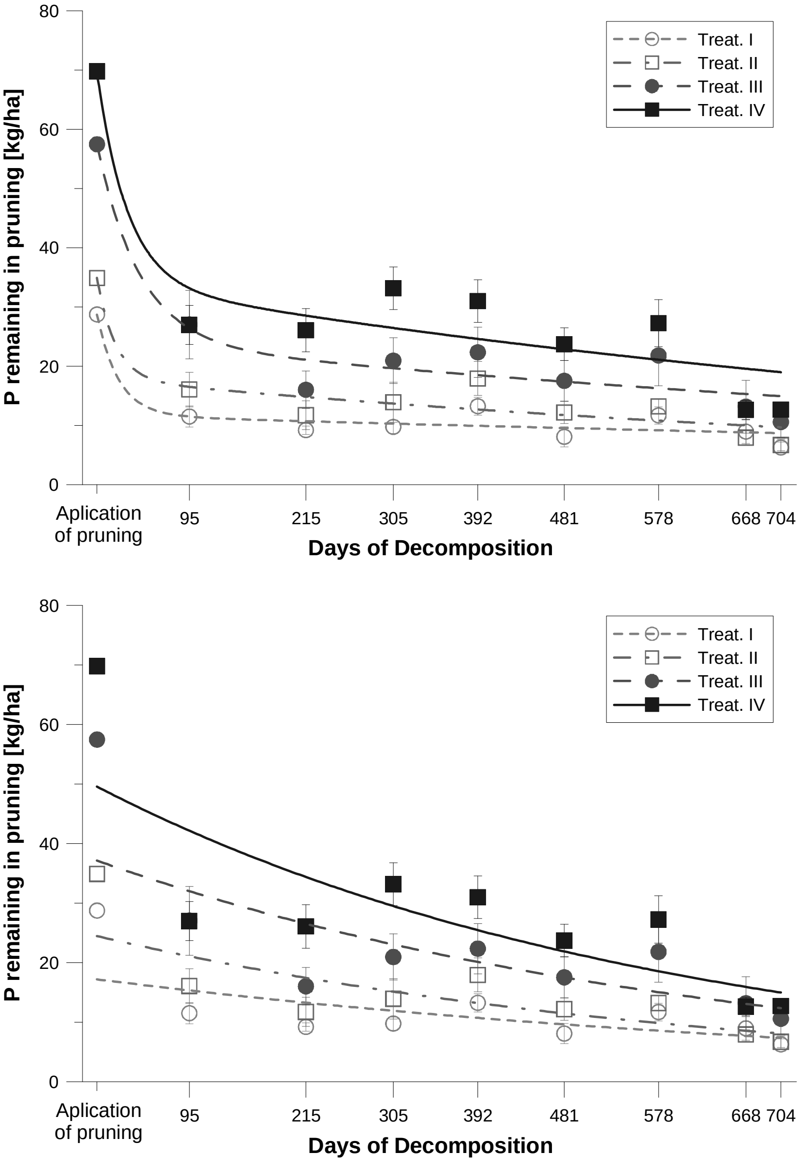

Fig. V-2. Temporal evolution of kg of P in residue mass per ha of cover in the different pruning residue treatments considered in the study. A double exponential model (above) and a single exponential model (below) have been represented. Vertical lines represent the Standard Error.

In the case of P, a significant decrease in the concentration of this element in the residue remains was observed at the beginning of the period, followed by a gradual decline from the second sampling date onwards (Fig. V-2). A total of 0.69, 0.60, 0.75 and 0.65 of total P lost in treatments I, II, III and IV respectively, was released in the first year. After 704 days of decomposition, these differences lessened and the average concentration of P in the residue mass on the last sampling date ranges from 6.3 kg/ha in the case of treatment I to 12.7 kg/ha in treatment IV.

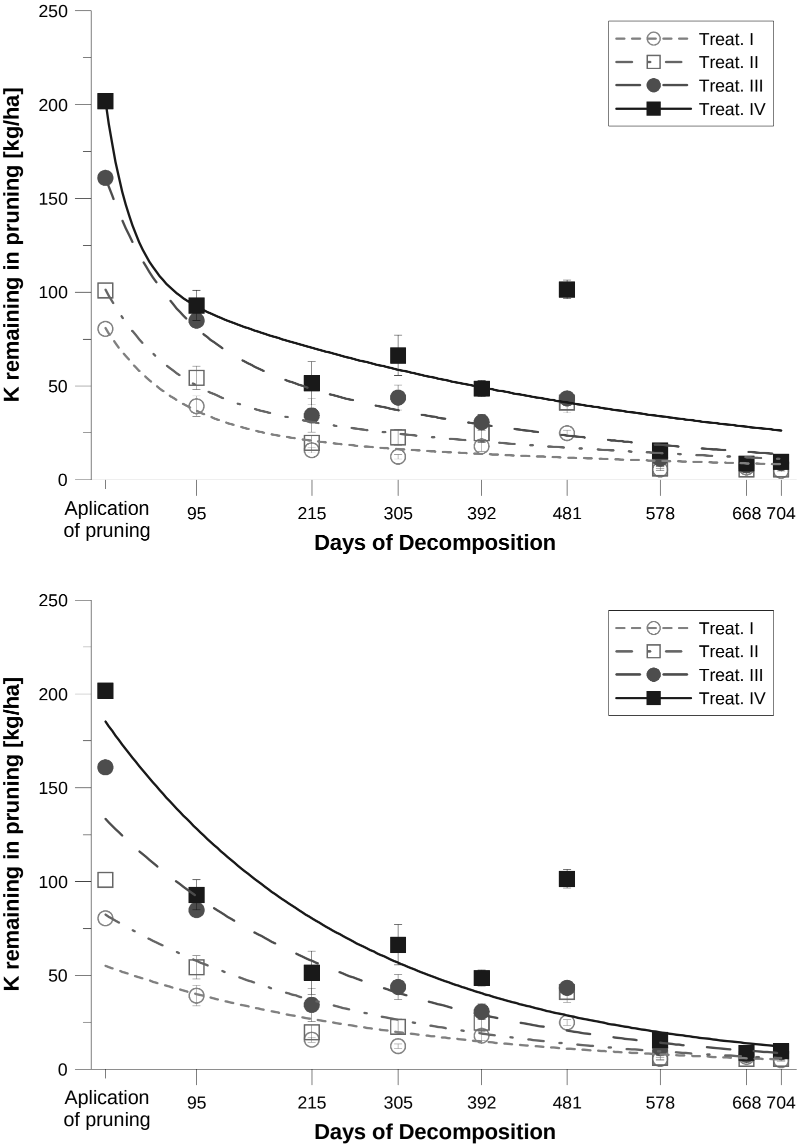

Fig. V-3. Temporal evolution of kg of K in residue mass per ha of cover in the different pruning residue treatments considered in the study. A double exponential model (above) and a single exponential model (below) have been represented. Vertical lines represent the Standard Error.

The K release rate was influenced by rainfall during the decomposition period and the decrease in the concentration of this element in the residue mass over time was similar for all treatments (Fig. V-3). As in the previous case, the presence of fine residues in the composition of the residue mass led to a greater release of K in the first year of the experiment. During this period, the residue mass under treatments I, II, III and IV respectively lost 0.84, 0.80, 0.86 and 0.80 as proportion of the total amount of K released. Due to being highly soluble, the average concentration of K remaining in the residue mass at the end of the period was the lowest of all the nutrients and ranged from 4.5 kg/ha for the treatment that employed the least residues to 9.7 kg/ha for the maximum dose.

Tables V-5, 6 and 7 represent the fit of a single and double exponential model over time to the release of N, P and K during the decomposition of residue mass. In general terms, as the residue mass contains matter that does not decompose easily, such as cellulose, hemicellulose and lignin, all the nutrients fitted the double exponential model better and recorded higher determination coefficients than those registered by the single exponential model.

Table V-5. Fit of a double and single exponential model to N remaining in pruning (kg/ha). R^2: Coefficient of determination.

	DOUBLE EXPONENTIAL				**SINGLE EXPONENTIAL**	
Treatment	L	k_1 [1/days]	k_2 [1/days]	R^2	k [1/days]	R^2
I	0.19	50.7×10^{-3}	1.02×10^{-3}	0.97	1.21×10^{-3}	0.91
II	0.15	08.8×10^{-3}	1.15×10^{-3}	0.97	1.37×10^{-3}	0.94
III	0.22	15.4×10^{-3}	1.00×10^{-3}	0.72	1.73×10^{-3}	0.72
IV	0.15	50.0×10^{-3}	0.85×10^{-3}	0.71	1.21×10^{-3}	0.65

Table V-6. Fit of a double and single exponential model to P remaining in pruning (kg/ha). R^2: Coefficient of determination.

	DOUBLE EXPONENTIAL				**SINGLE EXPONENTIAL**	
Treatment	L	k_1 [1/days]	k_2 [1/days]	R^2	k [1/days]	R^2
I	0.59	45.8×10^{-3}	0.42×10^{-3}	0.92	1.21×10^{-3}	0.49
II	0.49	53.0×10^{-3}	0.86×10^{-3}	0.90	1.57×10^{-3}	0.68
III	0.58	23.1×10^{-3}	0.68×10^{-3}	0.94	1.57×10^{-3}	0.65
IV	0.50	32.7×10^{-3}	8.72×10^{-3}	0.89	1.70×10^{-3}	0.68

Table V-7. Fit of a double and single exponential model to K remaining in pruning (kg/ha). R^2: Coefficient of determination.

	DOUBLE EXPONENTIAL				**SINGLE EXPONENTIAL**	
Treatment	L	k_1 [1/days]	k_2 [1/days]	R^2	k [1/days]	R^2
I	0.59	45.8×10^{-3}	0.42×10^{-3}	0.92	1.21×10^{-3}	0.49
II	0.49	53.0×10^{-3}	0.86×10^{-3}	0.90	1.57×10^{-3}	0.68
III	0.58	23.1×10^{-3}	0.68×10^{-3}	0.94	1.57×10^{-3}	0.65
IV	0.50	32.7×10^{-3}	8.72×10^{-3}	0.89	1.70×10^{-3}	0.68

Pearson correlation coefficients were estimated between the dynamics of dry matter in the residue mass, that of the various nutrients and their relationships (Table V-8). The trend in N, P and K content of the various treatments of pruning residues was strongly related to the evolution of the biomass, with $P \leq 0.001$ in all cases.

The highest correlation coefficients were generally observed between the biomass and N. The coincidence between dry matter dynamics and N in the residue mass was due to the fact the proportion of this element remained practically unchanged throughout the entire cycle of decomposition, recording average values of 0.0085 and 0.0098 for the initial and final samples, respectively.

Table V-8. Pearson correlation coefficients between residue mass (kg/ha) and, N, P and K in kg/ha, and between C/N, N/P, N/K and P/K ratios for each treatment.

Pearson correlation Residue mass	**Treat. I**	**Treat. II**	**Treat. III**	**Treat. IV**
N	0.862	0.873	0.915	0.788
	(*P* ≤ 0.001)	(*P* ≤ 0.001)	(*P* ≤ 0.001)	(*P* ≤ 0.001)
P	0.629	0.809	0.747	0.740
	(*P* ≤ 0.001)	(*P* ≤ 0.001)	(*P* ≤ 0.001)	(*P* ≤ 0.001)
K	0.757	0.788	0.836	0.767
	(*P* ≤ 0.001)	(*P* ≤ 0.001)	(*P* ≤ 0.001)	(*P* ≤ 0.001)
C/N	0.518	0.370	0.146	0.055
	(*P* ≤ 0.01)	(*P* ≤ 0.05)	NS	NS
N/P	0.074	–0.004	0.143	–0.038
	NS	NS	NS	NS
N/K	–0.435	–0.513	–0.739	–0.589
	(*P* ≤ 0.01)	(*P* ≤ 0.001)	(*P* ≤ 0.001)	(*P* ≤ 0.001)
P/K	–0.408	–0.388	–0.619	–0.631
	(*P* ≤ 0.05)	(*P* ≤ 0.05)	(*P* ≤ 0.001)	(*P* ≤ 0.001)

NS, not significant.

V-3.4. Increase in soil nutrients

The effect of the evolution of the residues under the different treatments on the concentration of nitrogen, phosphorous and potassium in the soil was evaluated. One common practice in organic olive growing is to allow spontaneous weeds to grow as plant cover to protect the soil. For this reason, in order to estimate the real effect of the decomposition of pruning residues on the various nutrients considered, the values of N, P and K content of the control sample (spontaneous weeds) were subtracted from those estimated for the rest of the treatments. The result of this calculation is presented in Fig. V-4 and two depths were considered to assess the effect of pruning residues both on the soil surface and also at lower layers. In all cases the value of the standard error of the data was very high, which explains why no significant differences were observed between the treatments for any of the nutrients considered.

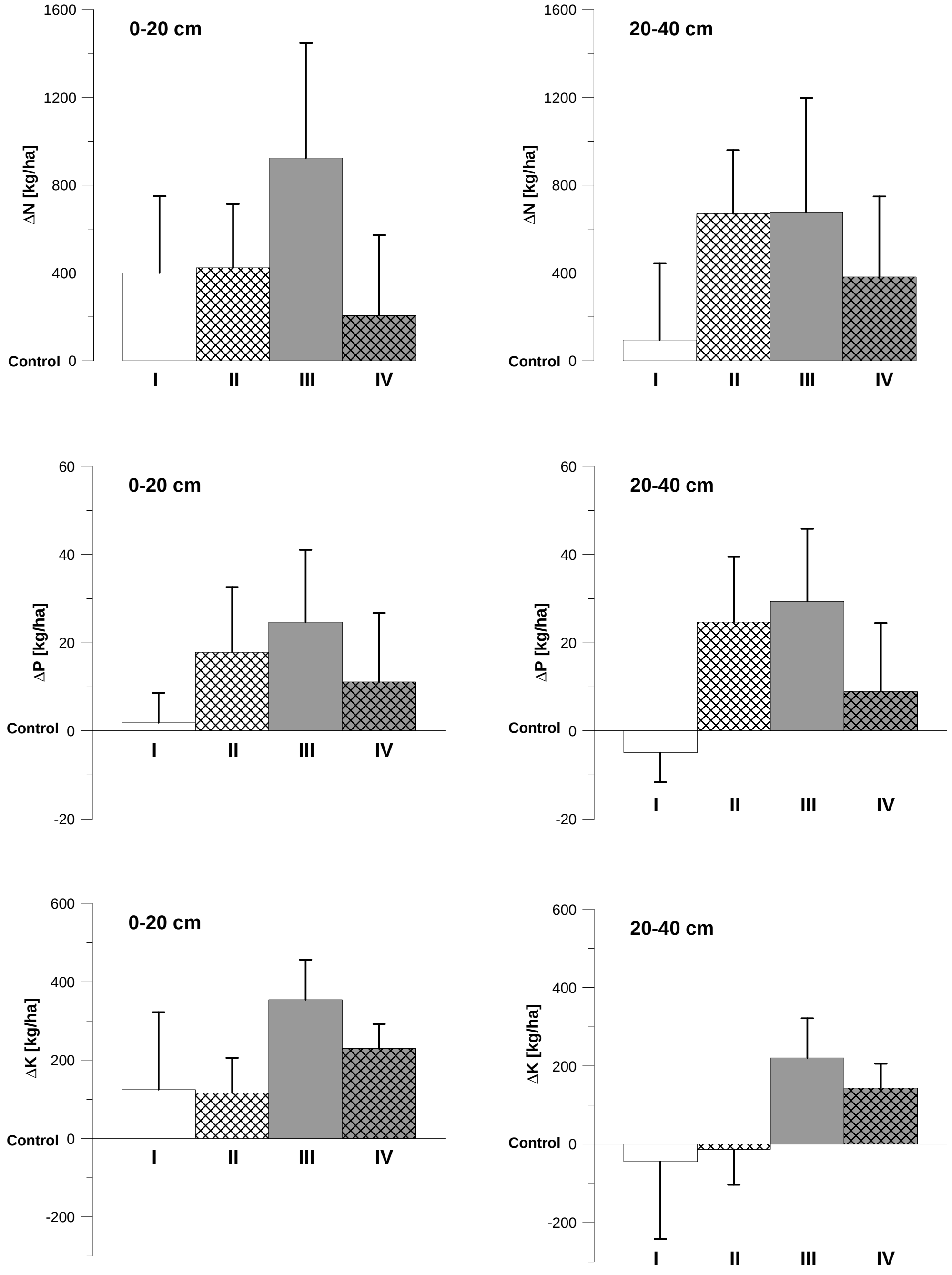

Fig. V-4. Increase in soil nutrients (N, P and K) in kg/ha between each treatment and the control, at depths of 0-20 and 20-40 cm. Vertical lines represent the Standard Error.

The concentration of N increased in all treatments and at all depths considered. On the soil surface (0–20 cm), the largest increase was observed under treatment III, where N concentration rose by 28.0% in regard to the control. As regards the rest of the treatments, increases of 13.0 (I), 13.7 (II) and 6.6% (IV) were recorded when compared to the control.

In the deepest layer of soil (20-40 cm), the amount of N in regard to the control generally increased by more than on the soil surface. Nutrient increases of 8.7%, 61.0%, 61.6% and 35.0% were registered for treatments I, II, III and IV, respectively.

The effect of pruning residue decomposition on P content in the soil surface differed markedly from one treatment to another. The smallest increase (4.6%) was recorded under treatment I, which involved the least amount of residues, while the largest increase (58.8%) was observed under treatment III, in which the largest quantity of residues were applied. In regard to treatments II and IV, which combine fine and thick residues, P increased by 44.7% and 27.9%, respectively.

The concentration of P at depth increased in regard to the control by 97.7%, 81.9% and 29.4% under treatments III, II and IV, respectively. Applying residues under treatment I apparently had no effect at this depth on the concentration of P, which actually recorded a lower portion than the control.

Meanwhile, the concentration of K on the soil surface increased in regard to the control by 12.7%, 11.8%, 27.0% and 23.4% under treatments I, II, III and IV, respectively. At depth, there was only an increase in the soil content of this element under treatments III (28.1%) and IV (18.3%). The treatments that involved less pruning residues (I and II) recorded a lower content of K than that estimated for the control.

V-4. DISCUSSION

V-4.1. Evolution of dry matter

Dose IV registered the smallest variation in biomass data, probably due to the fact that the high proportion of residue mass influenced the activity of micro-organisms that decompose plant residues. Authors such as Arrigo *et al.* (2005) have pointed out that excess plant residues applied to the soil can produce anaerobic conditions that limit residue decay.

According to ASAE (1998) standards, soil is considered to be protected during periods of critical erosion when at least 1120 kg/ha of residues are maintained on the soil surface. The residue mass under the various treatments and on the sampling dates was always maintained well above that limit, thereby ensuring soil protection at all times.

The largest quantity of biomass was lost during the first season. In fact, 0.77, 0.72, 0.62 and 0.57 of the total biomass was lost under treatments I, II, III and IV, respectively. During the decomposition process, the most labile organic compounds, such as sugars, starch and proteins, are easily degraded by micro-organisms in the soil, while other recalcitrant matter, such as cellulose, lignin and waxes have a slower decomposition rate (Aguilar 2005). The amount of residues applied also affected decomposition, as the largest percentage loss of biomass was recorded under treatment I (85%), which involves the least amount of residues.

No papers were found that allowed comparison of the biomass decomposition results of the current study to others that assess the behaviour of olive pruning residues. As regards other studies of perennial crop residues, the amount of dry matter remaining in the residues of treatment IV was similar to that indicated by Boniche *et al*. (2008) in a paper on the annual decomposition of palm stalks (*Bactris gasipaes*) and to the matter decomposed from oil palm tree pruning residues in Malaysia, regardless of whether it comes from plant biomass (Khalid *et al.* 2000*a*) or empty fruit bunches.

In a study on the decomposition of residues from different types of plant cover used in olive groves, Ordóñez *et al*. (2009) estimated an annual loss of biomass of 3110 kg/ha in the case of *Brachypodium distachyon,* 1350 kg/ha for *Eruca vesicaria* and 1540 kg/ha for *Sinapis alba.* All of those values were substantially lower than those recorded in the current study, although the proportions of decomposed residue were similar: 0.60, 0.46 and 0.49 respectively.

V-4.2. N, P, K release

Since micro-organisms can more easily decompose fine residues, treatments with fine pruning residues only released greater proportions of N.

The results obtained for this type of residue in one growing season contrast with those estimated by Rodríguez-Lizana *et al.* (2010) in a study on the release of N, P and K during the decomposition of more degradable residues such as pea (13.5, 2.9 and 9.9 kg/ha), wheat (6.7, –0.6 and 22.5 kg/ha) and sunflower (8.5, 0.7 and 78.0 kg/ha) in one growing season under similar climate conditions. Despite this, the proportions of nutrients released were usually higher than those obtained with the treatment of the current study: 0.77, 0.88 and 0.96 for pea; 0.48, –0.48 (immobilization) and 0.93 for wheat; and 0.56, 0.63 and 0.98 for sunflower. In the first year, the proportions of nutrient released ranged between 0.27 and 0.81.

In a study on the annual decomposition of palm stalks, Boniche *et al*. (2008) indicated similar N release values to those in the current study, but higher values in the case of P and K. In addition, for *Acacia mangium* residues, Ngoran *et al*. (2006) obtained losses of K of > 80%.

Ordóñez *et al*. (2009) assessed the mineralization and release of nutrients from the residues of various herbaceous species used as plant cover in olive groves over one growing season, finding that *Brachypodium distachyon* released 81.6, 7.3 and 78.2 kg/ha (82, 85 and 94% released), *Eruca vesicaria* released 24.3, 3.4 and 33.4 kg/ha (58, 61 and 86% released) and *Sinapis alba* released 21.5, 3.5 and 8.6 kg/ha (56, 68 and 67% released) for N, P and K, respectively. These amounts contrast with those indicated in the current study and highlight how important the choice of cover is when it comes to achieving improvements in the soil.

V-4.3. Evolution of N, P, K and models

The amount of nutrients released from pruning residues and the timing of this process during decomposition is very important for improving soil fertility (Mendoça & Stott 2003). The release of N, P and K from the residue mass as it decomposes fitted a downwardly exponential model, which took into account the amount of nutrient that remains in the residue mass throughout the period of decomposition. This type of model is related to the existence of various chemical constituents of differing resistance to degradation contained in the material. In this sense, the readily decomposable constituents degrade rapidly, as indicated by Wilson & Hargrove (1986), who studied the release of nitrogen and carbon from crimson clover residues. Similar results were obtained with Leucaena pruning residues in a shaded coffee agroecosystem by Youkhana & Idol (2009).

Authors such as Rovira & Vallejo (1997) contemplated single and double exponential models, among others, in their studies of decomposition using *Eucalyptus globulus*, *Quercus ilex* and *Pinus halepensis* buried at depth.

The studies performed by Aguilar & Staver (2001) found that the decomposition of stalks in agroforestry systems such as coffee were better suited to the double exponential model, which distinguishes two components, a labile fraction that decomposes easily and a recalcitrant component that degrades more slowly. Isaac *et al*. (2000) reached the same conclusion in a study on the decomposition and nitrogen release of pruning from Leucaena species. These authors' results coincide with those obtained in the current study.

In the case of N, treatments I, II and III displayed a good fit to the aforementioned model with determination coefficients that were very close to one in all cases. Treatment IV did not fit the model as well due to the large amount of residues applied to the soil under this treatment. Possibly, the activity of microorganisms at the beginning of the decomposition process was negatively influenced. Schlesinger (2000) and Soto *et al.* (2002) found the increase in microbial biomass of colonising organisms can immobilize them in the residue mass.

As in the previous case, P and K fitted the double model better. In this case, there was a clear difference between treatments that only contain fine pruning residues, which recorded determination coefficients close to one, and those which combine fine and thick residues, which registered lower determination coefficients.

Authors such as Schomberg & Steiner (1999), in studies on the release of nutrients contained in herbaceous crops that are difficult to decompose, observed disparate behaviour of P in comparison to other elements, even detecting that the microbial biomass had immobilized this nutrient. This is due to this element being released more slowly by the residue mass, resulting in a concentration of P. Furthermore, in conditions in which dry matter is released slowly, structural P can be retained by glucophosphates, nucleotides and mainly by phospholipides of the cellular membrane (Salisbury & Ross 1992).

In the double exponential model, the constant k_1 which regulates the decomposition of the labile fraction is generally greater than that estimated in the simple model, and k_2 which contemplates the evolution of recalcitrant compounds was lower in most cases. Authors such as Weerakkody & Parkinson (2006) indicated that in the case of residues with a high C/N ratio, as is the case in the current study, up to three phases can be distinguished in the release of nutrients: an initial phase in which soluble compounds are rapidly released, dominated by washing processes, followed by a phase of immobilisation and finally by a net release phase. Tian *et al*. (1992) stated that the C/N ratio is the main indicator of microbial activity.

In the simple exponential model, the release constant k was similar for N and P under all treatments and lower than that recorded for K. Similarly, this element registered the highest k_2, which indicates that despite being present in the most recalcitrant fractions of the residue mass, it is released rapidly due to being in ionic and mobile form inside the cytoplasm. The fact that K compounds are more soluble means the climate has a greater effect on the loss and release rate of this element, which accelerate when it rains. These results were similar to those reported by Delgado & Follet (2002) who stated that K is not associated with organic C and is leached out by rainfall.

The ease with which residues release K during decomposition when rainfall conditions are favourable was described in other studies with similar characteristics to the current one (Zaharah & Bah 1999; Cobo *et al.* 2002). The rapid release of K could be attributed to its presence in mobile cations in the cell fluid, which are released upon disintegration of cell membranes (Jordan 1985; Castellanos-Barliza & León Peláez 2011). Khalid *et al.* (2000*a*) and Lim & Zaharah (2000) also indicated a high K release rate and a low N release rate in studies on the decomposition of residues from various organs of oil palm.

The results of k_1 and k_2 obtained in the model for P and K remaining in the pruning residues were lower than those indicated by Bossa *et al*. (2005) in a study on decomposition and phosphorus and potassium release patterns from Leucaena leaves in three environments: these authors obtained values of 1.52 and 1.26 for k_1 and 0.024 and 0.075 for k_2 for P and K, respectively.

The composition of the residue mass played a vital role in the amount and speed at which nutrients were released. Khalid *et al.* (2000*a*) obtained a release rate for N in a study on oil palm residues that was much higher in the case of leaves than for other organs such as rachis, petioles and stalks, which contain less readily decomposable compounds. Aguilar (2005) reached similar conclusions in an analysis of data from decomposition and mineralisation trials with plant residues in coffee plantations.

The high degree of correlation observed between the dry matter of the residue mass and the elements analysed suggests that if the concentrations were stable, monitoring the remaining biomass could be a good indicator for predicting nutrient release. This is more reliable in N and P than in K because its concentration in residue was less stable. Authors such as Ngoran *et al*. (2006), Martínez-Yrízar *et al.* (2007) and Prause & Fernández López (2007) found strong relationships between the loss of weight and some quality indicators (lignin, N, C, C/N content, among others) in studies on the decomposition of plant residues, which coincides with the results of the current experiment.

Nitrogen/potassium and P/K were negatively correlated with biomass under all the treatments and were also highly significant in most cases. The explanation for this is the high solubility of K, which causes the release of this element to accelerate when it rains, regardless of the state of decomposition of the pruning residues.

The relationship between the loss of N and P from the residue mass as the biomass decomposes was not significant in any of the cases. This could be due to the fact that these nutrients are generally associated to organic forms and that the exclusive presence of large size residues on the soil can slow down and delay decomposition. In fact, if residues are large (size), bacteria and fungi have little penetration power and practically can only grow on the external surface (Alvear *et al*. 2008).

V-4.4. Increase in soil nutrients

After nitrogen, potassium is the element that is most used in fertilizing olive trees (Pastor *et al*. 2006). The amounts of nutrients necessary for the plant depend to a great extent on the characteristics of the plantation. The potassium demand of an olive grove is around 15 kg K_2O/1000 kg olives, identical to that of N and in contrast with the 4 kg P_2O_5/1000 kg olives (Domínguez-Vivancos 1993; Tombesi *et al*. 2002).

Phosphorus can be immobilized by microorganisms and this process plays an important role in maintaining the levels of this element in the soil (Ngoran *et al*. 2006), as in the case of treatment I at depth (20–40 cm).

In most cases, the nutrients of treatments with pruning residues increased, with respect to the control, at depth (20–40 cm) more than at the surface. This could be due to the fact that processes that affect the content of a soil nutrient, such as erosion, leaching, fixation, volatilization, denitrification, immobilization and absorption by other components of the agroecosystem, such as spontaneous weeds, are more intense on the soil surface, as Khalid *et al*. (2000*b*) observed in a study on the effect of oil palm residue decomposition on the soil content of nutrients.

The decomposition of the plant cover residues increased the medium or long-term levels of nutrients in the soil, as reported by Soria *et al*. (2000) in a study on the content of K and its relationship to the properties of 227 olive grove plots.

Ordóñez *et al.* (2007) also observed change in the content of nutrients in a study that assessed the modification in soil properties: the soil in an olive grove where pruning residues were applied for six years was compared to a non-tilled olive grove where the soil was left bare. Unlike the current study, Ordóñez *et al.* (2007) found an increase in the content of total N, available P and exchangeable K in the first 15 cm of the soil profile. At greater depths, the results did not favour the soil treated with residues, probably due to the constant application of residues every year affecting the capacity of microorganisms to decompose them.

Authors such as Ouro *et al*. (2001), Merino Barrios *et al*. (2003) and Zas & Serrada (2003) performed studies on the effect of applying pruning residues from *Pinus radiata* plantations to the soil surface on soil properties, obtaining an increase in the main nutrients on the soil surface. Youkhana & Idol (2009) obtained increases in soil C and N with Leucaena pruning residues mulching in a shaded coffee agroecosystem. Brañas *et al*. (2000) performed a study on the application of residues from various plantations of *Eucalyptus globulus* in order to provide information towards helping to design both the management of slash residues and also the duration of application turns, highlighting the improvement in soil fertility this practice has led to

V-5. CONCLUSIONS

Planning the use of tree residues must consider not only the amount available, but also the provision of nutrients that the operation brings about in the agricultural system. Under the conditions of the study performed for the current paper, the quantity, composition and quality of the residue mass had a great influence on the parameters monitored.

One of the problems that restricts the productivity of organic systems is that they cannot correct the lack of nutrients in the soil by applying synthetic fertilizers. Another problem is that herbicides cannot be used to control the weeds, so tillage is usually the preferred method of soil management. In view of the results obtained in the current study, a high dose of fine and thick residues, like the treatment IV, is recommended when the goal of the farmer is to keep the soil protected from erosive agents. However, a treatment of only fine residues in a high dose, as in treatment III, would be more suitable in order to improve the soil fertility in a short to medium term, in accordance with the edaphoclimatical conditions in the region, while still complying with the standards that govern this type of farm system. The release of nutrients during the decomposition of pruning was better fits to a double exponential model, which includes a labile fraction and another recalcitrant fraction that degrades more slowly.

V-ACKNOWLEDGEMENTS

To the field workers and laboratory personnel from the soil physics and chemistry team at Centro IFAPA Alameda de Obispo for their cooperation during the field trials, the Department of Innovation, Science and Enterprises of the Regional Government of Andalusia for their financial support through the Project of Excellence RNM 03-205 and the project RTA2010-00026-C02-01 financed by INIA as part of the "Subprograma Nacional de Recursos y Tecnologías Agrarias en Cooperación con las Comunidades Autónomas" (National Subprogram of Resources and Agricultural Technologies in Cooperation with Regional Governments), which at the same time is part of the National Research, Development and Technological Innovation Plan (R&D&I) and cofunded by the European Union through the ERDF.

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Chapter VI.

Summary, Resumen and General Conclusions

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VI-1. SUMMARY

The majority of the world's olive production is concentrated in the Mediterranean basin. Problems of erosion and loss of soil fertility pose a particular threat to the sustainability of this crop. In comparison to tillage systems, cover crops have proven to be an effective way of protecting the soil and producing improvements in its organic matter content.

The aim of this thesis is to gain a better understanding of cover crops, in particular in terms of which species most reduce runoff and erosion losses, and which have the most positive effect on soil fertility. The study was carried out with plant species typically used as covers: graminoids, crucifers and legumes. Dead mulches, which to date have been the focus of limited study, were also analysed. Such covers include pruning residues and their benefits were examined in relation to different amounts and residue size.

The existence of a vegetation cover, whether sown or spontaneous, reduces runoff and erosion losses. The study carried out using a sprinkler rainfall simulator on 50 m^2 plots with a 20% slope showed that the cover crop system significantly reduces soil loss and loss of soil organic carbon (SOC) associated with sediment wash-off. The experiment was carried out over two years with two rainfall intensities (40 mm h^{-1} and 15 mm h^{-1}) and at two different times of the year (when the cover crop is growing and after it has been mechanically mowed). The results showed that with a cover crops system runoff was reduced by more than 60% compared to a tillage system, and that there were reductions of soil and SOC loss of more than 90%.

In addition to protecting the soil against erosion and the associated loss of organic matter, cover crops offer other advantages such as improved physical and chemical properties of the soil as well as contributing to the capture and fixation of atmospheric carbon in the soil. A study was carried out over three seasons on a farm in southern Spain in order to assess the degree of protection during the period of decomposition of the cover after mechanical mowing, and the release of C to the soil. Three species, a gramineous plant (*Brachypodium distachyon*) and two cruciferous (*Eruca vesicaria* and *Sinapis alba*), were compared with the spontaneous vegetation in the area, which is the cover most widely used by farmers.

The decomposition of the cover crops released between 2.4 y 4.7 t ha^{-1} of C, depending on the species, with *B. distachyon* being the species that generated most biomass and best protected the soil throughout the decomposition period.

The climate of the area exerts a significant influence on the growth of the cover crops and thus on the benefits they provide. In fact, meteorological conditions in the third season meant that the gramineous species did not develop as it had in previous seasons, leaving *S. alba* as the species that fixed the most C as SOC in the soil profile studied.

A dead mulch of pruning residues protects the soil for a longer period of time, as it decomposes more slowly. Our study confirms that coverage did not drop below 60% in any of the different treatments tested in an experiment carried out over two seasons (704 days). The treatments involved the use of fine chopped residue (leaves and twigs of up to 8 cm) from spur pruning, as well as both fine and thick residue from a renewal pruning.

The decomposition of these residues and their nutrient release revealed a better fit to a double exponential model than to a single exponential model. This was because the residues contain both labile and recalcitrant fractions, which are not decomposed by microorganisms at the same rate.

The treatments with only fine residues and a high amount of biomass resulted in a higher rate of release of C and other nutrients except P. In the soil profile studied, all treatments increased the concentration of SOC, N, P and K compared to spontaneous cover. Although the treatment with the greatest amount of residues (both fine and thick) resulted in the highest percentage of covered surface area, the treatment with the greatest quantity of fine residues gave better results in terms of soil fertility.

Covers play an important role in terms of environmental sustainability, as they protect the soil and the decomposition of their residues promotes soil fertility.

VI-2. RESUMEN

En la cuenca mediterránea se concentra la mayor parte de la superficie mundial de olivar. La sostenibilidad de este cultivo está amenazada especialmente por problemas de erosión y pérdida de fertilidad de sus suelos. Las cubiertas han demostrado ser un sistema de cultivo eficaz para proteger el suelo del olivar y favorecer la mejora de su contenido en materia orgánica en comparación con el sistema de laboreo.

El objetivo que se pretende con esta tesis doctoral es tener un mayor conocimiento sobre las cubiertas vegetales, en concreto qué especies reducen más la escorrentía y las pérdidas por erosión, y cuáles son más favorables para mejorar la fertilidad del suelo. El estudio se ha desarrollado con especies vegetales típicamente empleadas como cubierta: gramíneas, crucíferas y leguminosas. Se ha trabajado también con cubiertas inertes, poco estudiadas hasta la fecha, como son los de restos de poda, valorándose los beneficios del uso de distintas dosis y tamaño de restos.

La existencia de una cobertura vegetal, ya sea sembrada o espontánea, reduce las pérdidas por escorrentía y erosión. El estudio desarrollado mediante un simulador de lluvia por aspersión en parcelas de 50 m^2 y una pendiente del 20% demostró que el sistema de cubiertas reduce de forma significativa las pérdidas de suelo y las pérdidas de soil organic carbon (SOC) asociadas al sedimento arrastrado. En el experimento, desarrollado durante dos años con dos intensidades de lluvia (40 mm h^{-1} y 15 mm h^{-1}) y en dos momentos del año (con la cubierta en su desarrollo y tras su desbroce mecánico), la escorrentía se redujo más de un 60% con el sistema de cubierta y las pérdidas de suelo y SOC en más de 90% respecto al sistema de laboreo.

Además de la protección del suelo contra la erosión y la pérdida de materia orgánica que ésta supone, las cubiertas vegetales tienen otras ventajas como la mejora de las propiedades físico-químicas del suelo y contribuir a la captura de carbono atmosférico y su fijación en el suelo. Para evaluar el grado de protección en el periodo de descomposición de la cubierta tras su desbroce mecánico y la liberación de C al suelo, se realizó un estudio desarrollado durante tres campañas en una finca del sur de España. Se emplearon tres especies, una gramínea (*Brachypodium distachyon*) y dos crucíferas (*Eruca vesicaria* y *Sinapis alba*), que fueron comparadas con la hierba espontánea de la zona, la cual es la cubierta más ampliamente utilizada por los agricultores.

La descomposición de la cubierta liberó entre 2.4 y 4.7 t ha^{-1} de C según la especie, siendo *B. distachyon* la que más biomasa generó y mantuvo el suelo mejor protegido a lo largo del periodo de descomposición.

La climatología de la zona tiene gran influencia en el desarrollo de las cubiertas y por extensión sobre los beneficios que proporcionan. De hecho, las condiciones meteorológicas de la tercera campaña provocaron que la gramínea no se desarrollara como en las anteriores y el *S. alba* fijó la mayor cantidad de C en forma SOC en el perfil de suelo estudiado.

Una cubierta inerte de restos de poda mantiene el suelo protegido durante un mayor periodo de tiempo ya que su descomposición es más lenta. Nuestras experiencias han confirmado que la cobertura no bajó del 60% en los distintos tratamientos de un experimento realizado durante dos campañas (704 días). Los tratamientos consideraban restos triturados finos (hojas y ramas de hasta 8 cm) procedentes de una poda de fructificación, y restos finos y gruesos generados en una poda de renovación.

La descomposición de estos restos y su liberación de nutrientes se ajustó mejor a un modelo doble exponencial que a un modelo exponencial simple, ya que en su composición estos restos contienen fracciones lábiles y recalcitrantes que presentan mayor o menor dificultad a la descomposición por los microorganismos.

El tratamientos con sólo restos finos y alta cantidad de biomasa obtuvo una mayor tasa de liberación de C y nutrientes salvo para el caso del P. Todos los tratamientos aumentaron la concentración de SOC, N, P y K respecto a la hierba espontánea en el perfil de suelo considerado. Aunque el tratamiento con mayor cantidad de restos (finos y gruesos) mantuvo el más alto porcentaje de superficie cubierta, el tratamiento con la mayor cantidad de sólo restos finos tuvo mejores efectos en cuanto a fertilidad de suelo.

Las cubiertas suponen una herramienta para la sostenibilidad del medio manteniendo el suelo protegido y favoreciendo la fertilidad con la descomposición de sus restos.

VI-3. GENERAL CONCLUSIONS

1. The low levels of cover associated with a conventional tillage system leads to considerably greater losses from runoff and soil erosion compared to cover crop systems. Significant results have been achieved through the use of cover crops, both sown and spontaneous, reducing runoff by more than 60% and soil and SOC loss by more than 90%.

2. Runoff hydrographs from experimental data are well suited to the kinematic wave model adopting a variable infiltration rate, especially in high-intensity rainfall, high-volume runoff events.

3. The powerful root system of cruciferous plants and their rapid biomass development facilitates infiltration. As a result, the *Sinapis alba* species reduces both water and soil loss much more than the other cover crops tested.

4. The spatial and temporal variation of cover residues is more stable with gramineous plants and pruning residues, although the residues must be spread evenly so as to minimise unprotected surface area.

5. The exponential model put forward by Gregory showing the relationship between cover and residue mass of cover crops is a better fit than the quadratic model. Calculating the coefficient of coverage *k* for each species of cover crop allows us to estimate coverage for a known residue mass during the period of decomposition.

6. Cover crops perform a dual function: they protect the soil from agents of erosion and facilitate soil fertility by increasing SOC through CO_2 fixation. In the study carried out over a three-year period using residues from live cover crops, the species *Brachypodium distachyon* achieved the highest percentage of soil cover, while *Sinapis alba* produced the greatest increases in SOC in the soil profile tested.

7. Although spontaneous, naturally-occurring vegetation is the most widely-used type of cover crop by farmers, other types of cover crop offer greater advantages in terms of soil protection: they provide greater and more stable percentage coverage over time; they release more carbon due to their greater biomass; and they fix more atmospheric carbon by sequestration.

8. Pruning residues, when used as dead mulch instead of being burned, provide effective and long-lasting soil coverage. Their high biomass means that they release a large quantity of carbon and nutrients, which consequently increases the content of these elements in the soil. This is particularly important in the case of organic olive groves where deficiencies in certain elements cannot be quickly replenished using artificial fertilizers.

9. To model the decomposition of pruning residue and the release of nutrients, a double exponential model is recommended. It separates the faster decomposing labile fractions from slower decomposing recalcitrant fractions. Due to the different rates of degradation of its components, the highest levels of biomass loss are recorded at the start of the decomposition period.

10. Treatments using chopped pruning residue from two rows of olive trees and applied in the space between two rows (treatments III and IV of our study) proved to be more effective at providing a greater and more consistent soil cover over time, if both coarse and fine residue was used. When only fine residue was used it also improved soil fertility.

11. In the same way that crop rotation is recommended for herbaceous crops, cover crop rotation between rows of permanent crops brings with it advantages such as avoiding soil compaction or flora inversion. It also makes better use of environmental resources, protecting the soil by preventing erosion, improving soil fertility and facilitating atmospheric carbon fixation.

12. For the most part, the deployment of cover crop systems will be subsidised at a regional, national or European level in the future, just as they are now. In addition to research, knowledge transfer and training for farmers are essential for the implementation of such systems.