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THE POTENTIAL OF CONSERVATION AGRICULTURE TO MITIGATE CLIMATE CHANGE IN MEDITERRANEAN AREAS

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TÍTULO DE LA TESIS: THE POTENTIAL OF CONSERVATION AGRICULTURE TO MITIGATE CLIMATE CHANGE IN MEDITERRANEAN AREAS

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INFORME RAZONADO DE LOS DIRECTORES DE LA TESIS

Los directores de la tesis Prof. Dr. Gregorio L. Blanco Roldán y Dra. 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 *Institute for Advanced Studies and Research* (IIFA) de la Universidad de Évora, Portugal, en dos periodos: junio-septiembre 2011 y junio-septiembre 2012. La tesis se presenta en capítulos, que se corresponden con tres publicaciones aceptadas en revistas indexadas (*Science of the Total Environment* y *Soil and Tillage Research*).

El proyecto en el que se enmarca la tesis (LIFE+ Agricarbon "Agricultura Sostenible en la Aritmética del Carbono" - LIFE08 ENV/E/000129), y del que el doctorando ha sido el director, ha sido empleado por la Oficina Española de Cambio Climático para justificar los datos del Inventario Nacional de Emisiones frente a los auditores de las Naciones Unidas; ha recibido el XVII Premio Andalucía de Medio Ambiente en la modalidad de "Mejor Proyecto Contra El Cambio Climático"; ha sido galardonado en el VII Congreso de Agroingeniería, como mejor presentación en la sesión dedicada a Producción Sostenible; y se ha identificado como "Caso de Éxito de Economía Verde", en la VII Conferencia Ministerial "Medio Ambiente para Europa" del Programa Medioambiental de las Naciones Unidas (UNEP).

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

Córdoba, 16 de noviembre de 2015

Firma de los directores

Fdo.: Prof. Dr. Gregorio L. Blanco Roldán

Fdo.: Dra. Rosa Mª Carbonell Bojollo

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La primera página es la última que escribo, recordando la parábola recogida en Mateo 20,1-16: "*los últimos serán los primeros*", que tiene su origen en un episodio agrícola. En este apartado, quiero corresponder en forma de agradecimiento a todas las personas que, tanto a nivel profesional como personal, han contribuido con su valía y sabiduría a que me haya sido posible llegar a este instante.

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Volviendo un poco la vista atrás, sólo unos 16 años de nada, en la época en la que a los agrónomos se nos contrataba antes de terminar la carrera, el día que defendí mi Proyecto Fin de Carrera, mi amigo Armando Martínez me propuso cambiar de aires, y unirme a la AEAC.SV. Gracias Armando por esa oportunidad, y por enseñarme a afrontar la agricultura en lenguaje bruselense, germen de tantos proyectos LIFE. Gracias también a Luis García Torres y Pedro González por confiar en mis posibilidades, por aquel entonces muy, muy incipientes. También merecen una mención especial en estos agradecimientos los profesores Gottlieb Basch de la Universidad de Évora-ECAF, y Amir Kassam, de la FAO-Universidad de Reading-ECAF, por contar conmigo en tantas iniciativas internacionales.

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CONTENTS

Chapter III. Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture 59

LIST OF PICTURES

Chapter I

LIST OF FIGURES

Chapter I

Chapter II

Chapter III

Chapter IV

LIST OF TABLES

Chapter II

Chapter III

Chapter IV

ANNEXES

Annex I.

Annex II.

Annex III.

Chapter I.

Introduction, hypothesis and objectives, and structure of the thesis

Chapter I. Introduction, hypothesis and objectives, and structure of the thesis

I-1. INTRODUCTION

Agriculture will play a key role in the coming decades, and will have to deal with strategic global concerns. Among the most serious environmental threats related to agriculture, there can be found the degradation of soils; water quality and availability and mitigation and adaptation to climate change. Somehow, the environmental pressures are interlinked, which is underpinned by experimental evidence and in the literature as well (Kassam et al., 2012). In this thesis, the links between a sustainable soil management and the mitigation of climate change will be demonstrated.

The pursuit of sustainability is a common objective all over the world. In the report of the World Commission on Environment and Development: Our Common Future, also known as the Brundtland Report (United Nations, 1987), it was shown that the road taken by society was destroying the environment, at the same time leaving more people vulnerable and in poverty. Indeed, the Brundtland Report was the first attempt to eliminate the conflict between development and sustainability. Nowadays, the definition of sustainable development proposed in that report is commonly accepted: “sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs”. According to FAO, in 2050 there will be more than 9 billion people on the planet. It is commonly recognized that sustainable development calls for a convergence between the three pillars of social equity, environmental protection and economic development. Certainly, in our era the world is changing at a dramatic pace, where economic and social development does not always correspond with a respect for natural resources, which are essentially limited. Moreover, feeding the growing population, without exhausting natural resources will be a challenge, especially when even today about 795 M people are undernourished globally (FAO, 2015a).

With regards to climate, the World Meteorological Organization ranked 2014 as the hottest year on record, as part of a continuing trend. In fact, 14 out of 15 of the hottest years have been in the 21st Century (WMO, 2015). Human influence on climate change is clear and accepted among the scientific community. Undoubtedly, recent anthropogenic emissions of greenhouse gases (GHG) are the highest in history, as anthropogenic GHG emissions have increased since the pre-industrial era. This has led to atmospheric concentrations of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O) that are unprecedented in at least the last 800,000 years. When large quantities of GHG such as CO_2, CH_4, and N_2O are released into Earth's atmosphere, they can trap solar radiation, raising global and regional temperatures and altering entire climate systems.

Carbon dioxide is the GHG most commonly produced by human activities and it is accountable for 64% of human-made global warming. Its concentration in the atmosphere is at present 40% higher than it was when industrialization began. Other GHG are emitted in smaller quantities, but they trap heat far more effectively than CO_2, and in some cases are thousands of times stronger. Methane is responsible for 17% of man-made global warming, nitrous oxide for 6% (European Commission, 2015a). Total anthropogenic GHG emissions have continued to increase over from 1970 to 2010 with larger absolute increases between 2000 and 2010 despite a growing number of climate change mitigation policies. Anthropogenic GHG emissions in 2010 have reached 49 ± 4.5 Gt CO_2-equivalents year^{-1}. Emissions of CO_2 from fossil fuel combustion and industrial processes contributed to about 78% of the total GHG emissions increase from 1970 to 2010, with a similar ratio influence for the increase during the period 2000 to 2010. The Intergovernmental Panel on Climate Change (IPCC) stated in their Fifth Assessment Report that the anthropogenic drivers are extremely likely to have been the dominant cause of the detected warming since the mid-20th century (IPCC, 2014). In fact, each of the last three decades has been continuously warmer at the Earth's surface than any previous decade since 1850. In particular, the period from 1983 to 2012 was likely the warmest 30-year period of the last 1400 years in the Northern Hemisphere. Moreover, the globally averaged combined land and ocean surface temperature data as calculated by a linear trend show a warming of 0.85 [0.65 to 1.06] ºC over the period 1880 to 2012 (IPCC, 2014).

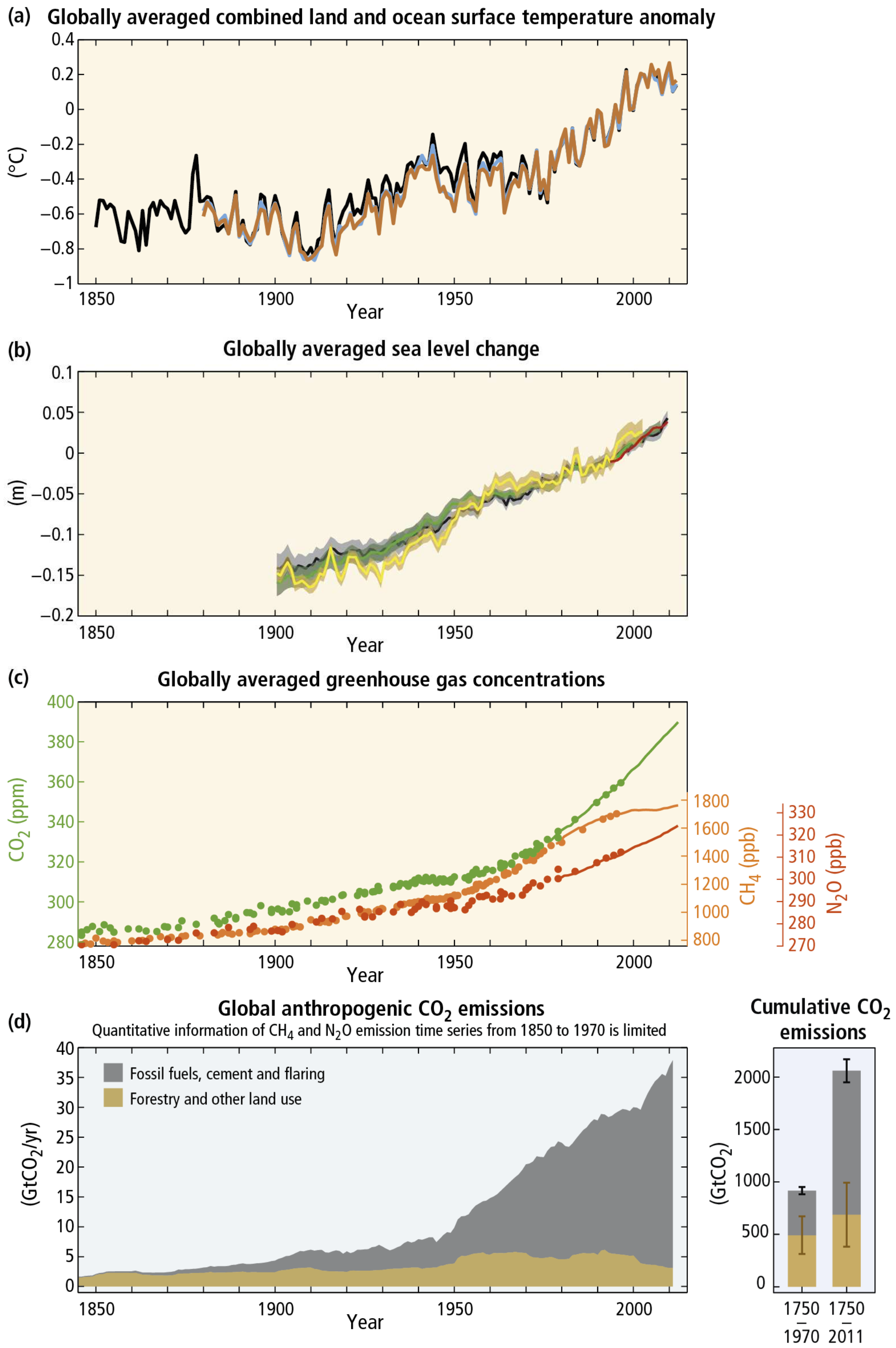

Figure I.1. Observations and other indicators of a changing global climate system. Source (IPCC, 2014).

(a) Annually and globally averaged combined land and ocean surface temperature anomalies relative to the average over the period 1986 to 2005. Colours indicate different

data sets. (b) Annually and globally averaged sea level change relative to the average over the period 1986 to 2005 in the longest-running dataset. Colours indicate different data sets. All datasets are aligned to have the same value in 1993, the first year of satellite altimetry data (red). Where assessed, uncertainties are indicated by coloured shading. (c) Atmospheric concentrations of the GHG carbon dioxide (CO_2, green), methane (CH_4, orange) and nitrous oxide (N_2O, red) determined from ice core data (dots) and from direct atmospheric measurements (lines). Indicators: (d) Global anthropogenic CO_2 emissions from forestry and other land use as well as from the burning of fossil fuels, cement production and flaring. Cumulative emissions of CO_2 from these sources and their uncertainties are shown as bars and whiskers, respectively, on the right hand side.

Around 10% of the GHG emitted worldwide in 2012 came from the European Union (EU). According to the European Environmental Agency, the EU's share of global emissions is falling (EEA, 2014). This is due to two reasons; on one hand, Europe is reducing its own emissions, and at the same time, those from other parts of the world, especially the major emerging economies, continue to grow. For 2020, the EU has committed to reducing its emissions to 20% below 1990 levels (European Commission, 2014). The EU's '20-20-20' goals focus on: a 20% reduction of the EU's GHG emissions compared to 1990; a 20% share of renewable energy sources in the EU's gross final energy consumption; a 20% saving of the EU's primary energy consumption compared to projections. These targets form part of the Europe 2020 growth strategy, alongside targets relating to employment, education, research and innovation, and social inclusion and poverty reduction (European Commission, 2015c). In the EU-28, GHG emissions stood at 4,678.8 M Mg CO_2-equivalents in 2012. This figure marked an overall reduction of 17.9 % when compared with 1990, or some 1,017 M Mg of CO_2-equivalents. Currently, about 9% of total EU GHG gas emissions come from agriculture, down from 11% in 1990. The European Environment Agency in its report No. 13 published in October 2012, stated that emissions of GHG in the agricultural sector in 2011 accounted for 9.9% of total emissions of the EU-27, constituting the fourth issuance activity in the whole EU behind the power sector, transport and industrial combustion processes.

With regard to Spain, the estimated emissions for 2013 of the total inventory stood at 319.6 M Mg CO_2-equivalents, which represents an increase over the 1990 base year of 10.9%. In Spain, agriculture and livestock represent 14% of the total emissions and 22% of the emissions of the diffuse sectors.

Agriculture both contributes to climate change and is affected by it. In agriculture and forestry, photosynthesis favours the C incorporation into carbohydrates. This process is key to mitigate climate change, as crops capture CO_2 from the atmosphere during photosynthesis by converting C forms associated with soil organic matter (SOM) for microbial decomposition processes (Johnson et al., 2007). On the other hand, agricultural activities, such as ploughing tasks and the use of fertilizers, favours the emission of CO_2 and N_2O. In Spain, the emissions from agricultural soils, which represent half of the emissions from the agricultural sector, emissions from manure management, and emissions resulting from the use of fuel for agricultural machinery have special relevance (MAGRAMA, 2015a).

Climate change will affect European agro-ecosystems. In particular, for the Mediterranean region, climate change simulations predict a pronounced decrease in precipitation, especially in the warm season. A pronounced warming is also projected, at maximum in the summer season. Inter-annual variability is projected to mostly increase especially in summer, which, along with the mean warming, would lead to a greater occurrence of extremely high temperature events (European Commission, 2015b). The intensity and robustness of the climate change signals produced by a range of global and regional climate models suggest that the Mediterranean might be an especially vulnerable region to global change (Giorgi and Lionello, 2008). Throughout the EU in general and in the Mediterranean area in particular, a serious problem due to climate change looms. Impacts are expected at various levels, which will be especially adverse for agricultural ecosystems and may result in a decline in crop productivity. Moreover, in some parts of the Mediterranean area, due to extreme heat and water stress in summer months, some summer crops might be cultivated in winter instead.

The EU has expressed the need to mitigate climate change and adapt to its impacts. For that reason, it has promoted several initiatives: the new Common Agricultural Policy (CAP), by Regulation 1305/2013, in its Article 5, promotes resource efficiency and encourages a shift towards a low carbon economy and ability to adapt to climate change in the agricultural, food and forestry sectors. The strategy looks for a more efficient use of energy in agriculture, to reduce emissions of GHG and ammonia from agriculture, whilst recommending conservation and carbon sequestration in the agricultural and forestry sectors. At the same time, the Regulation 1306/2013, includes an area of the environment, climate change and good agricultural condition of the land within the annex which regulates cross-compliance standards. Furthermore, the importance of carrying out measures for reducing CO_2 emissions within the agricultural sector in order to mitigate climate change is acknowledged by the Committee on Agriculture and Rural Development of the European Parliament, through the document 2009/2157 (INI) on “EU agriculture and climate change”.

The Kyoto Protocol (United Nations, 1998) established that carbon sequestration in agricultural soils may be calculated as a negative when counting CO_2 emissions (Article 3.4). Therefore, carbon sequestration in soils is a mechanism which Europe can use to meet their emission targets. In this way, enhanced agricultural practices may be key to reducing emissions of GHG, whilst capturing atmospheric carbon and governments have the power to promote better agricultural practices through several administrative tools. The most powerful in Europe is the CAP. Since the reform of Agenda 2000, the CAP is divided into two pillars: the pricing policy and markets, namely the Common Market Organisation (CMO) (Pillar 1) and rural development policy (Pillar 2). Since the last reform 2014-2020, the introduction of a Greening Payment, where 30% of the available national envelope is linked to the provision of certain sustainable farming practices, a significant share of the subsidy will in future be linked to rewarding farmers for the provision of environmental public goods. Moreover, the agri-environmental schemes (included in Pillar 2) are also an option to reward environmentally friendly agriculture, as farmers commit to following practices that go beyond conventional farming practices, and in return receive an extra subsidy for a period of five years. Soil is a natural resource which is usually taken into account in agri-environmental schemes, as it is a non-renewable natural resource with numerous functions in the maintenance of natural ecosystems and agricultural production.

Picture I-1. Erosion problems in annual crops.

It is expected that with climate change, overall yields in 2050 could decrease by 20 to 30 percent. Moreover, up to 50,000 km^2 of productive land is lost every year through soil erosion and land degradation processes; besides, many more have reduced yields and almost 3 M km^2 are considered at very high risk of desertification. This degradation could reduce the available cropland by 8–20% by 2050 (Giovannucci et al., 2012). Moreover, soil degradation processes have an enormous economic cost. An impact assessment carried out by the European Commission showed that soil degradation processes in Europe could cost up to € 38 billion a year (Van-Camp et al., 2004). Therefore, it is urgent to adopt best management practices, new technologies, farming methods, and supporting institutions to the world's farmers (United Nations, 2012). Best management practices that may impact soil conservation and soil quality, by increasing soil organic carbon, would have a direct influence on climate change. Consequently, a good soil management strategy is key not only for preventing soil erosion from occurring, but also for mitigating climate change.

Picture I-2. Conservation agriculture in annual crops. Winter wheat in no-tillage.

Picture I-3. Conservation agriculture in perennial crops. Groundcovers between rows of orange trees.

Globally, a study alerting the loss of one third of the arable surface of the globe in the past few decades, at a rate of about 10 M ha per year (Pimentel et al., 1995). In Europe, there are over 157 M ha seriously affected by any sort of soil degradation (ECAF, 1999), which will increase in future years according to the prediction by the different scenarios of climate change, especially in areas with little protective cover. The Thematic Strategy for Soil Protection (COM (2006) 231 final) and the proposal Soil Directive (COM (2006) 232), which was withdrawn in May 2014, identify the threats at European level, highlighting among others, the loss of organic matter, erosion and compaction. Those problems are related to the use of ploughs in conventional tillage practices. Degradation through erosion processes is especially alarming in the agricultural area, again mainly due to the intensive conventional tillage system, which is the most commonly used soil management system. Furthermore, erosion produces substantial reductions in soil carbon. The loss of soil causes a reduction in organic matter and fertility. In addition, while the soil is eroded and loses fertility, its ability to retain moisture falls thus increasing desertification, which is particularly severe in semiarid areas like the European countries of the Mediterranean basin (Kassam et al., 2012). If rainfall decreases in the area, not only will soil conservation be crucial, but so too improved water management.

In addition to N_2O emissions resulting from the use of fertilizers, main GHG emissions in agriculture are those of CO_2 due to the tillage of the soil. Tillage causes substantial losses of soil C, which range from 30% to 50% (Davidson and Ackerman, 1993). These losses are due to the carbon fragmentation caused by the tillage of the soil, which facilitates biological activity, resulting in an exchange of O2 and C between the soil and the atmosphere and vice-versa. Soil management in conventional agriculture consists of a primary inversion tillage with a mouldboard plough or a chisel plough, followed by various surface secondary tillage operations with cultivators or disk harrows. With these field operations, famers are able to bury the plant debris and leave the ground disaggregated to facilitate easy seeding. Unfortunately, the soil is left in optimal conditions for CO_2 losses to occur, while drastically reducing soil sink effect.

Soil conservation techniques, such as conservation agriculture, meets the demands of today's agricultural scenario, both technically and at the legislative level. The use of conservation agriculture is recognized positively to mitigate and adapt to climate change (Lal et al., 2011), whilst helping farmers interested in saving production costs in the medium term (FAO, 2015b). Nevertheless, in the past, some agri-environmental schemes have subsidized so-called environmentally friendly practices that are not supported by scientific evidence. An example is the Spanish Rural Development Program 2000-2006, where the measure number 4 was named "Erosion in fragile environments" (MAGRAMA, 2015b). The main objective of this measure was to protect the soil, avoiding losses due to erosion in agricultural areas with steep slopes. However, although many technical requirements were aligned to avoid erosion, reduced tillage was accepted without any obligation of leaving at least 30% of soil covered after planting, which is critical to conserve soil effectively (CTIC, 1994).

It is therefore necessary to identify agricultural systems that are truly sustainable, that respond to environmental challenges such as climate change and soil conservation. In addition, assessing the potential of good agricultural practices for large-scale implementation is essential, in order to evaluate the environmental benefits that could be achieved.

I-2. HYPOTHESIS AND OBJECTIVES

The hypothesis is that practices that can be included under the conservation agriculture principles have a positive effect on the mitigation of climate change, by both increasing soil organic carbon, and by reducing the emissions of CO_2 into the atmosphere.

The main objectives (O1, O2, and O3) of the thesis are to:

- Define conservation agriculture practices that can be promoted in European programs related to the environment, agriculture and climate change (O1).

- Evaluate the potential of conservation agriculture to mitigate global warming in Mediterranean climate zones,
    - by assessing soil as a carbon sink potential in the area (O2), and
    - by comparing CO_2 emissions released under conventional farming vs no-tillage (O3).

Those objectives have been achieved and justified in the three peer reviewed articles, as follows:

- O1 in the article: Gonzalez-Sanchez, E.J., Veroz-Gonzalez, O., Blanco-Roldan, G.L., Marquez-Garcia, F., Carbonell-Bojollo, R., 2015. A renewed view of conservation agriculture and its evolution over the last decade in Spain. Soil and Tillage Research, 146 (PB), pp. 204-212. http://dx.doi.org/10.1016/j.still.2014.10.016

- O2 in the article: González-Sánchez, E.J., Ordóñez-Fernández, R., Carbonell-Bojollo, R., Veroz-González, O., Gil-Ribes, J.A., 2012. Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture. Soil and Tillage Research, 122, pp. 52-60. http://dx.doi.org/10.1016/j.still.2012.03.001

- O3 in the article: Carbonell-Bojollo, R., González-Sánchez, E.J., Veroz-González, O., Ordóñez-Fernández, R., 2011. Soil management systems and short term CO_2 emissions in a clayey soil in southern Spain. Science of the Total Environment, 409 (15), pp. 2929-2935. http://dx.doi.org/10.1016/j.scitotenv.2011.04.003

I-3. STRUCTURE

This thesis is divided into five chapters. Three of them comprise published papers in indexed journals. Soil & Tillage Research –Chapter II and Chapter III- and Science of the Total Environment –Chapter IV.

- Chapter I: Introduction, hypothesis and objectives, and structure of the thesis.
- Chapter II: A renewed view of conservation agriculture and its evolution over the last decade in Spain.
- Chapter III: Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture.
- Chapter IV: Soil management systems and short term CO_2 emissions in a clayey soil in southern Spain.
- Chapter V: Summary and general conclusions.

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Chapter II.

A renewed view of conservation agriculture and its evolution over the last decade in Spain

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Chapter II. A renewed view of conservation agriculture and its evolution over the last decade in Spain

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II-ABSTRACT

The interest in conservation agriculture in Spain is evidenced by practical and institutional aspects. The practical aspect is reflected by the area cultivated under this farming system, 1.28 M ha in perennial crops and 0.57 M ha in arable crops, both for 2013. The period under review was 2009–2013 for arable crops and 2006–2013 for perennial crops. In that period, figures increased 208% for no tillage in arable crops, and 54% for groundcovers in perennial crops. The institutional support is reflected by the financial funding given to conservation agriculture farming practices by some Spanish Regional Governments, primarily through Rural Development Programs, that reached over € 200 million in the 2000–2006 period. The origins of soil conservation practices date back to the 1930s and have evolved in parallel in America and Europe. This parallelism has led to the use of different terminology for similar practices that do not always fall within the scope of conservationist practices. Consistent with the literature, and based on the results of 6 meetings with 144 Spanish experts, this paper aimed at clarifying terms and practices applied under the conditions of Spain, but could be useful for other geographies. This article also proposes definitions to clearly describe the different concepts for experts, advisers, and also for policy makers to accurately allocate funds in the European financial framework 2014–2020.

Keywords: No tillage, reduced tillage, groundcovers, conservation tillage, definitions.

II-1. INTRODUCTION

Conservation agriculture (CA) is one of the so-called emerging agrosciences (Lichtfouse et al., 2010) and encompasses techniques that minimize or eliminate tillage and, thus, maintain a vegetative cover that protects soil from its degradation. CA principles emanate from conservation tillage (CT), which includes no tillage (NT), reduced tillage (RT) and groundcovers (GC) in perennial crops (CTIC, 1994). Nevertheless, CA is not the same as CT. Certainly, CA concept goes beyond CT and is defined by three linked core principles that must be jointly applied to create synergies (Kassam et al., 2012): minimum soil disturbance; permanent organic soil cover; and crop rotations. CA relies on NT as the best practice for arable crops, and on GC for perennial crops.

In some way, CA intends to go back in time in terms of soil protection, as ancient cultures based their agriculture on planting in virgin soil using sticks or other sharp tools to make small holes in which to place the seeds (Derpsch, 1998). In the early 1930s, in the central plains of the United States of America, years of extreme drought resulted in intense wind erosion events known as the Dust Bowl, and millions of tons of soil were lost. These events were captured by Pare Lorentz of the United States Department of Agriculture (USDA) in the film “The Plow that Broke the Plains”, which documented the action of tillage as the main cause of erosion (Lorentz, 1936). In response, new tillage equipments to loosen the soil and control weeds without turning over the soil were developed in North America. Those new implements allowed to keep the plant residues on the surface of the soil. This method rapidly expanded throughout the dry lands in the U.S. In addition to fighting soil erosion, this practice better conserved soil moisture. Another milestone in the history of CA, was the foundation in 1935 of the US Soil Conservation Service. In the following years, the service encouraged the creation of research teams dedicated to CA in many American universities (Hill et al., 1994). Similarly, the release of the book Plowman's Folly (Faulkner, 1942) increased the sensitivity to the problems of excessive tillage and helped to spread the techniques of CA. During the 1940s, universities, the USDA and farming companies began an intense research plan that resulted in several advances. In1946, the University of Purdue developed the first seeder for NT, the M-21, and in the 1950s, the wavy disc blade and treatments with atrazine (2-chloro-4-ethylamino-6-isopropylamino-1,3,5-triazine) and paraquat (1,1'-dimethyl-4',4'-bipyridilium dichloride) were commercially introduced. In the 1960s, NT was presented as a viable technique for farming (McKibben, 1968).

In northern European countries, the combined negative effects of excessive tillage, particularly in wet soils, with the decline in the rural population and the increased costs of machinery, led many researchers to consider a reduction of tillage and to start experiments in Germany (Baeumer, 1970), the Netherlands (Ouwerkerk and Perdok, 1994) and the UK (Christian, 1994). Nevertheless, the lack of appropriate herbicides made weeds a limiting factor for the development of these tillage systems (Allen, 1981). This problem was overcome with the emergence of herbicides such as paraquat and diquat (1,1'-ethylene-2,2'-bipyridylium dibromide), developed by Imperial Chemical Industries (ICI) in the late 1950s. These products eliminated the need of tillage to control weeds because its total action eradicated them without risk for the subsequent crop. This approach made it feasible to replace tillage by the chemical control of weeds (Hood et al., 1963; Boon, 1965). Thus, the concept of NT arose when the ability to control weeds and equipment adapted to the presence of stubble on the surface of the soil were available. Despite these advances, the idea of entirely eliminating tillage was viewed with scepticism by farmers, and NT was restricted to research projects. It was not until the mid-1960s that the agronomic and economic advantages of these new techniques were perceived by a wider section of the agricultural sector (Moody et al., 1961), and as a consequence, new programs for developing and introducing these systems were initiated in several European countries.

In Spain, the first studies on CA in annual crops date back to 1976 and were performed in the "Haza del Monte" farm in Seville. In these trials that aimed at advancing the sowing date of a second crop, the NT of soybeans over previous crop residues were evaluated (Fernández Quintanilla, 1997). In Madrid, NT trials began in 1980 on the 'The Encín' farm and were carried out based on an agreement between the Technical School of Agricultural Engineers (ETSIA) of the Polytechnic University of Madrid and the National Research Institute for Agriculture and Food Technology. The results showed that NT did not affect grain yields and reduced 80% of energy consumption (Juste et al., 1981). This type of trial was extended to other Spanish regions, including those performed by the Agricultural Research Service of Andalusia and the ETSIA of the University of Cordoba in the 'Tomejil' farm in Carmona, Seville. These trials, which began in 1982 and still continue today, resulted in higher yields in NT fields than in those with traditional tillage (TT) (González et al., 2010). TT practices comprise the common passes of primary and secondary tillage for preparing the seedbed. The primary are deep tillage passes, and are usually performed with mouldboard or chisel ploughs, whereas the secondary passes are shallower than the primary ones, and are generally performed with cultivators or disk harrows. After all those tillage passes, the soil is bare. Another good example of NT that started in 1986 and is still active today, is the Malagón farm (López-Bellido, 2014). As well, several long term trials were conducted by the Technical and Farm Management Institute in Navarra, the Universtity of Lleida in Catalonia, the CSIC research station Aula Dei in Aragon, and the Research Institute of Castille and Leon. In some studies, it was remarkable the collaboration with the technical departments of the industry (Fernández Quintanilla, 1997). In February 1995, a group of farmers, technicians and scientists, many of them participants of the above-mentioned experiments, founded the Spanish Association for Conservation Agriculture and Living Soils. Thanks to the development of European funded projects, such as LIFE 99ENV/E/308 and LIFE 96ENV/E/338, and the support of manufacturers of NT machinery and the industry of plant protection products, a number of technology transfer activities were conducted with a high degree of regularity, still on-going currently.

Nowadays, the growing interest in soil conservation farming practices across the world is demonstrated by the expansion of NT. In 1999, 45 million hectares were cultivated using NT, whereas 125 million hectares in 2011. These figures represent about 9% of global cropland, and 14% of the cropland in the countries that have adopted NT (Friedrich et al., 2012). There is an evidence to predict a wide and imminent growth in major global economies, such as China (He et al., 2010). Globally, the reasons for this increase mainly derive from the economic benefits that NT practices entail, given the drastic reduction of mechanised operations and the subsequent drop in fuel consumption and working time (González Sánchez et al., 2010). During the expansion of CA systems, achievement of similar yield levels compared with TT has been demonstrated by multiple studies (Triplett et al., 1973; Van Doren et al., 1976; Phillips et al., 1980; Uri, 2000), and has been a major driver for farmers to shift to CA.

In Europe, CA is recognized as an effective practice to protect soil, and has been identified as a solution to serious environmental problems that affect European soils. An impact assessment, carried out in accordance with the European Commission's guidelines and on the basis of available data, shows that soil degradation could cost up to €38 billion a year (Van-Camp et al., 2004). To promote soil conservation practices, European Union's (EU) Member States have tools available, such as the National Rural Development Programmes (RDP), which are co-financed by the EU and its Member States. In Spain the RDPs supported some measures promoting CA during the period 2007–2013 (MAGRAMA, 2014a,b). In the previous RDP, which covered the period 2000–2006, the total budget was over € 1300 million. An example of annual investment is shown in Table II-1. In year 2006, all agri-environmental measures slightly exceeded € 201 million, whereas 27 million for CA measures. At the end of 2006, nearly 18% of farmers who adopted any agri-environmental measure in Spain received this support for practicing CA. These farmers accounted for 4.6% of the total area that adopted agri-environmental measures and 13.4% of the budget allocated to the RDP. In addition, other initiatives aimed at promoting the adoption of CA in Spain. CA has demonstrated to help Spain's authorities to meet the targets set in the Kyoto Protocol (González-Sánchez et al., 2012). Based on the actions to establish the potential for the sequestration of CO_2

throughout the Spanish territory as a result of changes in the use of agricultural land, the Spanish Office for Climate Change suggested the use of several agricultural practices to increase the soil's sink effect. These practices included a decrease in the intensity of tillage, an increase in the hectares of arable crops under CT and NT as well as an increase in the surface area of perennial crops with GC, among others (BOE, 2006). Nevertheless, not all agricultural practices contribute equally in carbon sequestration, whereas NT and GC were found always positive, RT may be positive or negative concerning its carbon fixation rates (González-Sánchez et al., 2012).

Table II-1. Financial support of total agri-environmental measures in Spain in 2006 and support of conservation agriculture measures. (Adapted from MAGRAMA, 2011b)

	Number of farmers	**%**	**Area (ha)**	**%**	**Public support (x 1,000 €)**	**%**
Total agri-environmental measures	98,502	100	3,034,511	100	201,996	100
Conservation agriculture measures	17,613	17.9	144,403	4.6	27,133	13.4
Perennial crops	16,943		141,190		26,959	
Arable crops	670		3213		174	

In Spain, the names and definitions of CA practices have been adopted from countries where this agricultural system was developed. This has led to the lack of accuracy of CA definitions. For instance, from the standpoint of machinery manufacturers, the interpretation of CA principles has resulted in conceptual problems such as the use of incorrect terms. As an example, small mouldboard ploughs that penetrate soil less than 15 cm, shallower than the traditional over 25 cm, are presented as RT equipment (Ovlac, 2014). Similarly, combination cultivator seed drill that prepares seedbeds with only one tillage operation, disturbing soil and leaving less than 30% of crop residue, is wrongly considered as NT equipment.

Due to the fact that CA has evolved in different parts of the world, diverse nomenclatures were coined for similar agricultural practices. As CA is practiced worldwide following different in-field methods, there is a need for the standardization of terms (Derpsch et al., 2014). This article intends to standardize the definitions of CA in Spain, and to present its evolution in perennial and arable crops in the country. CA definitions, and the clarification of terms used to describe the practices, also intend to serve as a basis for the further implementation of agri-environmental measures by the next RDP (2014–2020) of the Government of Spain and the Autonomous Communities of the country.

II-2. MATERIALS AND METHODS

For the definitions, the method used was based on the organization of meetings with Spanish experts. In total, 6 meetings were organized and different soil and climatic conditions were assessed (Fig. II-1) at the early stages of the 2007–2013 financial framework. The analyzed regions were Seville in the south, Albacete in the central-east, Madrid in the centre, Valladolid in the central-west, Zaragoza in the northeast and Lugo in the northwest.

Figure II-1. Map of Spain. Stars represent the locations where the meetings were held.

The expert groups comprised of researchers, advisers, officials of the Ministry for Agriculture and Environment, and farmers. For identifying researchers, authors consulted the database of the Thematic Network on Conservation Tillage AGF96-

1613-E funded by the Spanish Inter-ministerial Commission of Science and Technology (CICYT). For advisers, the authors contacted companies and private technicians collaborating with the CA movement in Spain. Finally, key farmers were contacted through national and regional CA associations; members with the most prominent historical commitment to the practice of CA were chosen. In total, 144 representatives participated in the meetings. As a result of the meetings, the definitions for the implementation and development of CA in Spain were agreed upon and are summarized in Section 3.

The evolution in the uptake of CA in Spain has been studied from official statistics of the Spanish Ministry for Agriculture, Food and Environment, based on surveys. The methodology for collecting data is fully described in MAGRAMA (2014b). As the full description is in Spanish, a brief summary is given here below. The survey is focused on the distribution of crops, land cover, and yields on cultivated land. Fieldwork for data collection is performed mainly between the first two weeks of May and the first week of August, according to a schedule designed taking into account the planting and harvesting of crops, and adapted according to their phenological stage. The purpose of this calendar is to enable the identification of arable crops sown in the fall and winter of the previous year, to be found close to its maturity phase, and for crops sown in spring, to be already established in order to correctly classify them at the time of the field visit. The sampling frame (Fig. II-2) is obtained by overlaying on the national territory the Universal Transverse Mercator (UTM) grid projection of Spain's topographic map. A frame dividing the territory in cells of 1 km^2 areas is established and after, those cells are integrated in blocks of 100 km^2. The basic sample comprises of 3 cells in each of the blocks, which always occupy the same relative positions within it, and are therefore, distributed uniformly throughout the territory to be investigated. This is the systematic sampling procedure. As a fieldwork unit, a square of 700 m on each side is taken, and attached to the lower left corner of the corresponding cell. Normally, the replacement of the sample cell by the segments barely alter the reliability of the results and makes field work easier. In order to strengthen the results, the method allows to study deeply the areas where many crops are present, by investigating 3 or more additional segments per block in areas where there is more crop diversity.

Data analyzed range from 2006 to 2013 in perennial crops, and from 2009 to 2013 in arable crops. In perennial crops, the survey considered as CA system areas where in the interrow spaces spontaneous vegetation is maintained, cover crops are sown or pruning residues are retained. For arable crops, only NT tillage has been considered as a valid CA technique. The fit of the regression models was made with the linear regression module in the program Statistix 8.

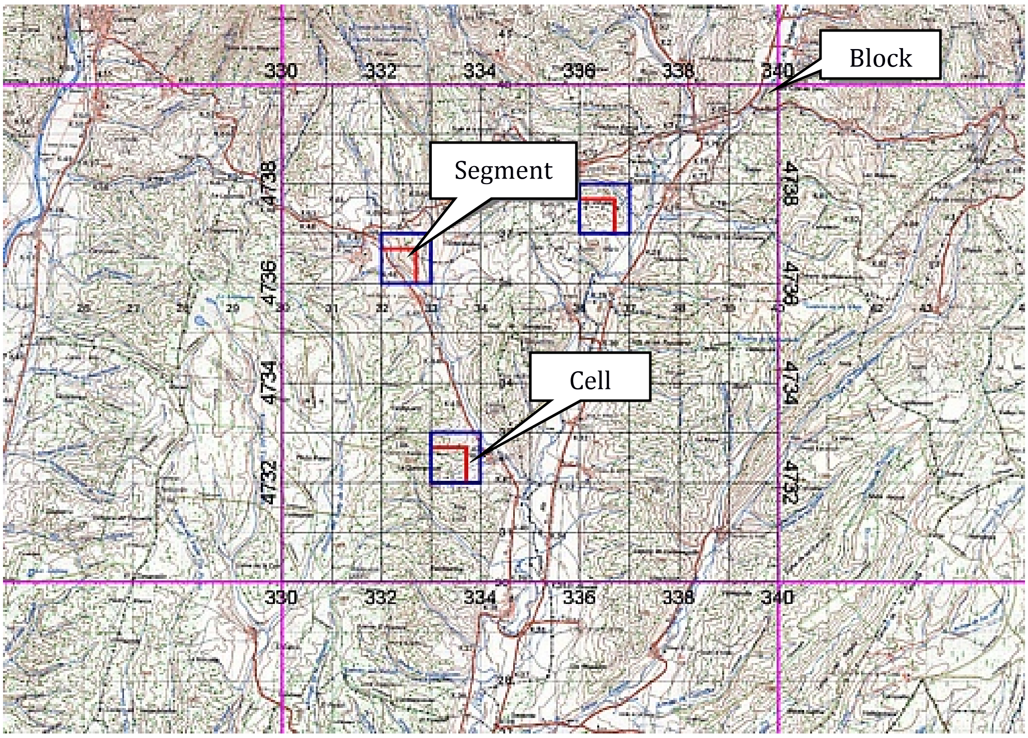

Figure II-2. Sampling frame used for assessing hectares under different soil management systems and concepts for the statistical planning. Adapted from MAGRAMA, 2007.

II-3. RESULTS

II-3.1. Definitions

As a result of the meetings, the following definitions for soil conservation practices in Spain were agreed among all participants.

II-3.2. Conservation agriculture

CA is defined as a sustainable agriculture production system comprising a set of farming practices adapted to the requirements of crops and local conditions of each region, whose farming and soil management techniques protect the soil from erosion and degradation, improve its quality and biodiversity, and contribute to the preservation of the natural resources, water and air, while optimizing yields.

Agronomic practices included in CA are based on three core principles, which must be fulfilled concomitantly:

- Minimum soil disturbance.
- Maintenance of permanent soil covers.
- Cropping system diversity, crop rotations.

II-3.3. No tillage

NT is a CA agronomic practice for annual crops, and is defined as a way to farm without disturbing the soil through tillage. NT must leave at least 30% of area covered by plant residues right after crop establishment, and crops are sown using a machinery which is able to place seeds through plant residues from previous crops.

The agronomic practice that best characterizes CA for annual crops is NT, which has the highest degree of soil conservation in annual crops, since the mechanical tillage of the ground is completely suppressed.

II-3.4. Reduced tillage

RT is defined as an agronomic practice in which the soil profile is only altered vertically. For being considered as a soil conservation practice, it must leave at least 30% of area covered by plant residues right after crop establishment. RT has a lower soil conservation grade than NT.

II-3.5. Groundcovers

GC is the most widely used CA agronomic practice for perennial crops, whereby the soil surface between rows of trees remains protected against erosion. With this technique, at least 30% of the soil not covered by the canopy is protected either by sown cover crops, spontaneous vegetation or inert covers, such as pruning residues or tree leaves. For the establishment of sown cover crops and the spread of inert covers, farmers must use methods in coherence with CA principle of minimum soil disturbance.

II-3.6. Evolution of conservation agriculture in Spain, 2006–2013

Regarding CA, Spain is the leading country in Europe. Fig. II-3 represents the official data of the adoption of CA for the country. It comprises the sum of NT and GC in the period 2009–2013. Fig. II-4 shows the evolution and adoption trend for NT since 2009, and Fig. II-5, the same for GC since 2006. In the period 1995–2009, assessment of NT adoption was performed based on indirect indicators such as the number of NT planters sold and an average area drilled per planter, and personal interviews with pioneers from diverse areas across the country. Pioneers consulted are members of regional associations of NT, and have access to the number of associates of the region, and know the average area drilled per farmer. Normally, the practice of GC in perennial crops is not included in international statistics that reflect the adoption of CA. In Spain, CA is practiced to a much larger extent in perennial crops when compared to arable crops, with 25.5% *vs.* 7.5% of the total area, respectively. In both cases, the implementation trend is positive and the expectations are high.

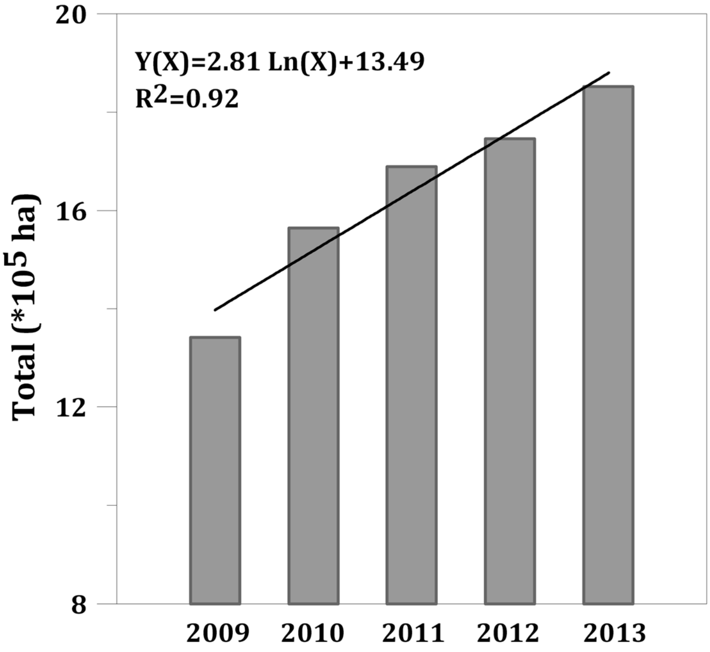

Figure II-3. Evolution of conservation agriculture in Spain (arable and perennial crops). Source: MAGRAMA, 2010; MAGRAMA, 2011a; MAGRAMA, 2012; MAGRAMA, 2013; MAGRAMA, 2014c.

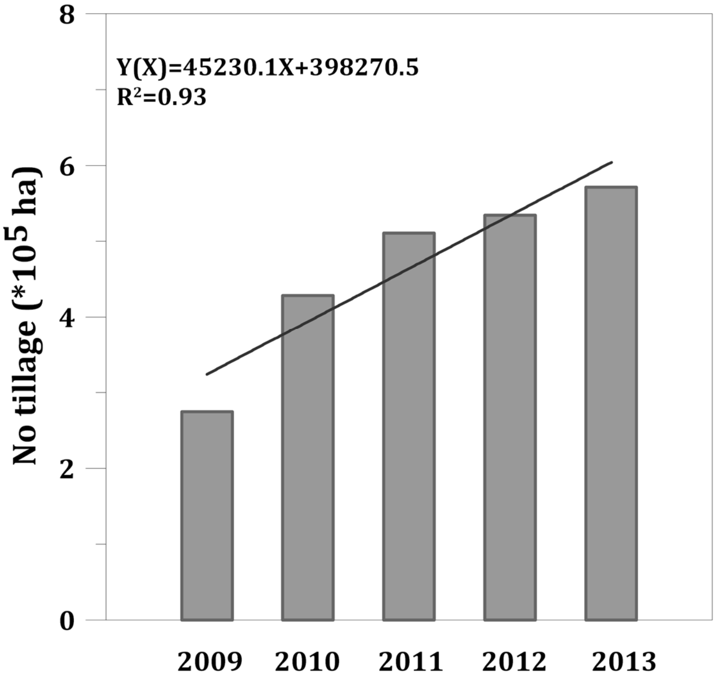

Figure II-4. Evolution of no tillage in arable crops in Spain. Source: MAGRAMA, 2010; MAGRAMA, 2011a; MAGRAMA, 2012; MAGRAMA, 2013; MAGRAMA, 2014c.

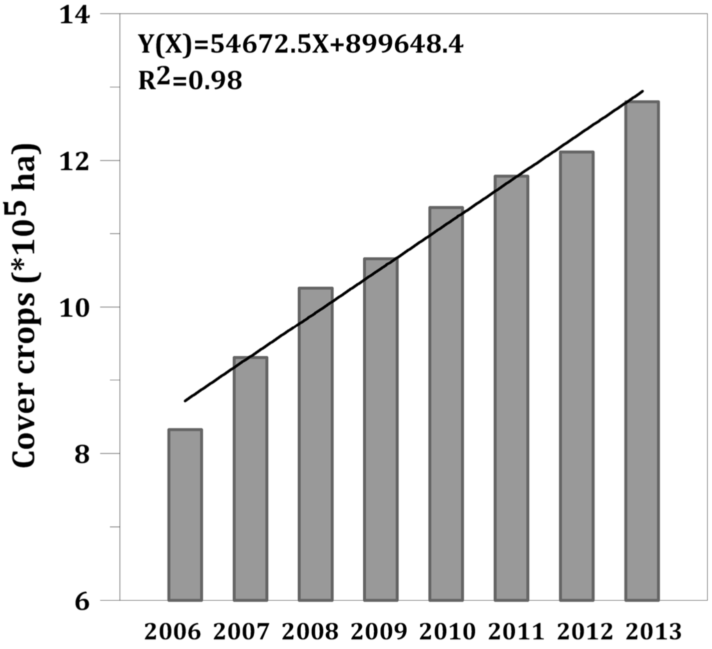

Figure II-5. Evolution of groundcovers in perennial crops in Spain. Source: MAGRAMA, 2007; MAGRAMA, 2008; MAGRAMA, 2009; MAGRAMA, 2010; MAGRAMA, 2011a; MAGRAMA, 2012; MAGRAMA, 2013; MAGRAMA, 2014c

In the next 2–3 years, NT is expected to reach 700,000 (9%) hectares and GC 1,400,000 (28%). Possible reasons for this growth are the increasing availability of specific machinery, incentives under agri-environmental schemes (2014–2020), and the soil protection promoted under the cross-compliance in the Common Agricultural Policy. Cross-compliance is a mechanism that links direct payments to compliance by farmers with basic standards concerning the environment, food safety, animal and plant health and animal welfare, as well as the requirement of maintaining land in good agricultural and environmental condition (European Commission, 2014). In the period under review, NT has increased 208%, while GC has grown by 54%.

As shown in Fig. II-6, in Spain main crops in NT are winter grains (barley and wheat); spring grains (corn); legumes (chickpea, beans, vetch); and oilseeds (sunflower). Fig. II-7 presents the area under CA in the main perennial crops, which are olive groves, fruits, citrus and vineyards. The types of covers used are shown in Fig. II-8, where a clear predominance of the use of spontaneous covers, with over 90%, can be observed. This is mainly due to the reduced costs for implementing that type of cover crop.

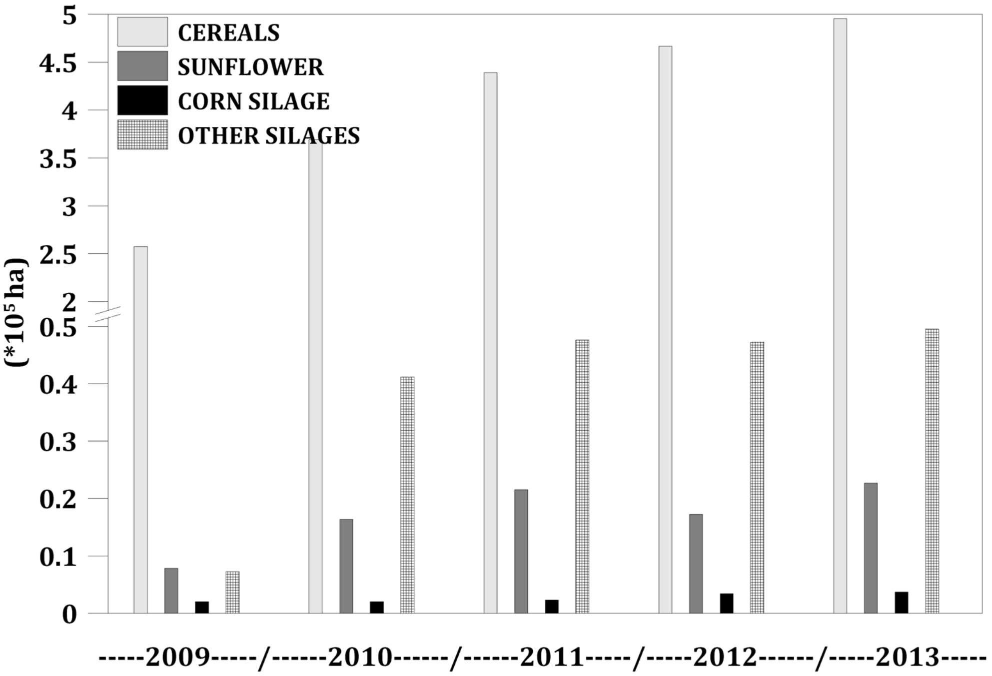

Figure II-6. Area of major crops under no tillage in Spain. Source: MAGRAMA, 2010; MAGRAMA, 2011a; MAGRAMA, 2012; MAGRAMA, 2013; MAGRAMA, 2014c.

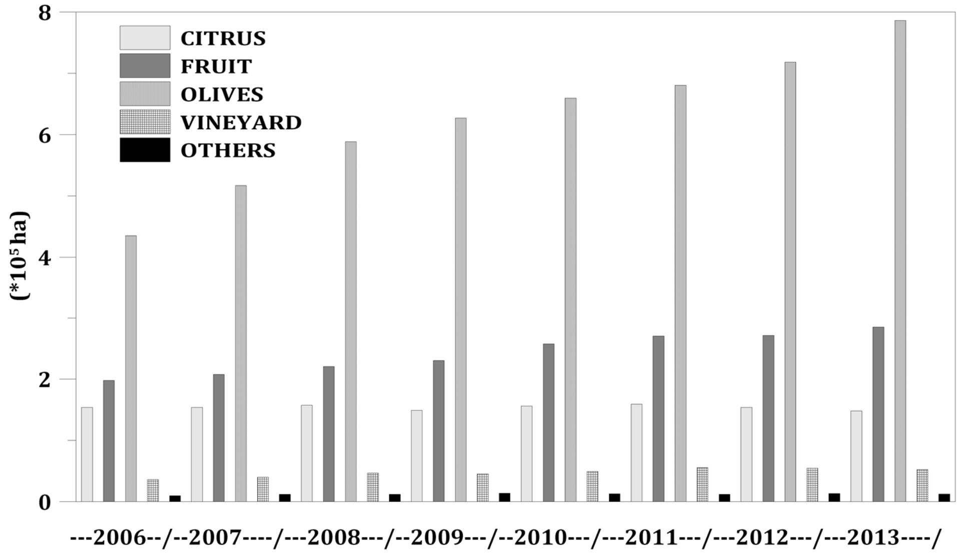

Figure II-7. Major perennial crops with groundcovers in Spain. Source: MAGRAMA, 2007; MAGRAMA, 2008; MAGRAMA, 2009; MAGRAMA, 2010; MAGRAMA, 2011a; MAGRAMA, 2012; MAGRAMA, 2013; MAGRAMA, 2014c.

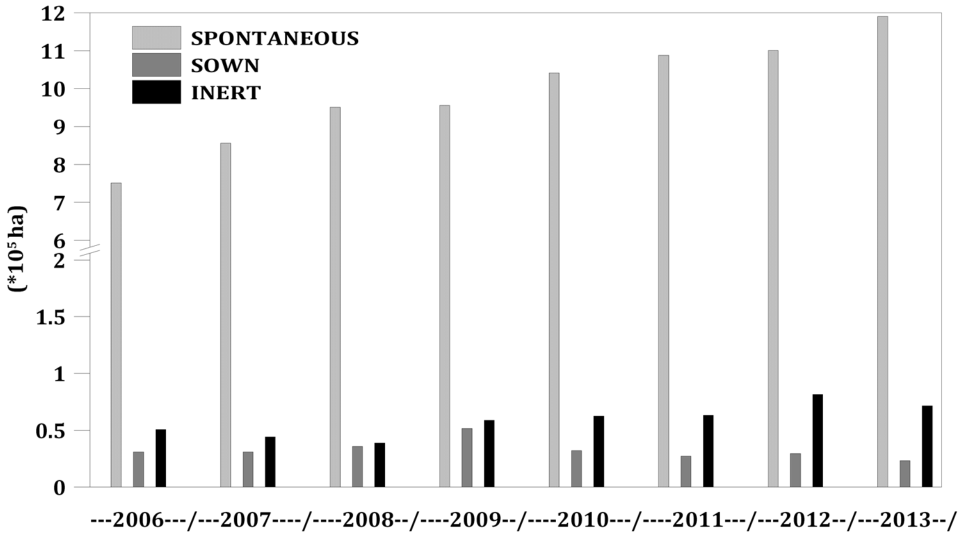

Figure II-8. Types of groundcovers in perennial crops in Spain. Source: MAGRAMA, 2007; MAGRAMA, 2008; MAGRAMA, 2009; MAGRAMA, 2010; MAGRAMA, 2011a; MAGRAMA, 2012; MAGRAMA, 2013; MAGRAMA, 2014c.

II-4. DISCUSSION

Table II-2 lists CA techniques and synonyms frequently used in the literature, and substantiates which fit into CA systems. Still, definitions in this paper are in coherency with the literature. A possible reason for the different names for essentially equal practices is the parallel development of soil conservation systems in America and Europe in the middle of last century, when the transfer of information was not as efficient as today.

II-4.1. Conservation agriculture vs. conservation tillage

CT is widely cited in literature. According to the Conservation Technology Information Center (CTIC, 1994), it is defined as follows.

> Conservation Tillage Types (30% or more crop residue left, after planting). Any tillage and planting system that covers 30% or more of the soil surface with crop residue, after planting, to reduce soil erosion by water. Where soil

erosion by wind is the primary concern, any system that maintains at least 1000 pounds per acre of flat, small grain residue equivalent on the surface throughout the critical wind erosion period.

Table II-2. Synonyms for so-called soil conservation agricultural practices found in the literature.

Type of crop	Technique	Synonym	CA	Comments
Arable	No tillage	No till; Zero tillage; Zero till; Direct drilling; Direct seeding; Direct sowing	Yes	If combined with permanent soil cover and crop rotations.
	Reduced tillage	Minimum tillage; Minimum till; Reduced till	No	Generally, the preparation of soil for planting needs 2-3 tillage operations. Less than 30% of soil is covered after seeding.
	Mulch tillage	Mulch till	No	The mulch is buried through tillage operations. Less than 30% of soil is covered after seeding.
	Strip tillage	Strip till	?	The equipment must be used accurately in order to qualify as CA. Generally, there is excessive soil or residue disturbance, so less than 30% of soil is covered after seeding.
	Ridge tillage	Ridge till	No	Building the ridge involves soil tillage in most of the surface. Less than 30% of soil is covered after seeding.
	Slot tillage	Slot till; Slot planting	?	The equipment must be used accurately in order to qualify as CA. Generally, there is excessive soil or residue disturbance, so less than 30% of soil is covered after seeding.
	Row tillage	Row till	No	Generally, excessive soil or residue disturbance. Less than 30% of soil is covered after seeding.
Perennial	Groundcovers		Yes	If combined with permanent soil cover.

Considering the reduced tillage of NT and the presence of protective soil cover, the FAO (2014) coined the term CA, introducing crop rotation in their principles and thus enhancing the biological improvement of systems.

> Conservation agriculture is a concept for resource-saving agricultural crop production that strives to achieve acceptable profits together with high and sustained production levels while concurrently conserving the environment. Conservation agriculture is based on enhancing natural biological processes above and below the ground. Interventions such as mechanical soil tillage are reduced to an absolute minimum, and the use of external inputs such as agrochemicals and nutrients of mineral or organic origin are applied at an optimum level and in a way and quantity that does not interfere with, or disrupt, the biological processes. Conservation agriculture is characterized by three principles which are linked to each other, namely:
>
> - Continuous minimum mechanical soil disturbance.
> - Permanent organic soil cover.
> - Diversification of crop species grown in sequence or associations.

CTIC (1994) included in CT: NT, RT, ridge-till and mulch-till. Thus, CT is an umbrella term for some soil management practices, as a number of agricultural practices may meet the requirements. USDA developed the Soil Tillage Intensity Rating (STIR) (USDA, 2014a). STIR is a numerical value calculated using RUSLE2 (USDA, 2014b), based on the factors determined by the crop management decisions being implemented for a particular field. Lower numbers indicate less overall disturbance to the soil layer. Values may range from 0 to 200 with a low score preferred. The STIR value reflects the kind of soil disturbance besides the intensity of disturbance caused by tillage operations. By definition, NT operations require a STIR value of 30 or less.

The main difference between CT and CA is that CT allows more tillage than CA. For instance, to fulfil CA core principles it is not possible to perform strip-till, mulch-till, or ridge-till. All of these would be allowed in CT. As well, neither RT should be recommended for CA; although RT is typically included in CT. Concerning residues over the soil, some practices included in Table II-2 may retain 30% of plant residues on the surface of the soil after planting and can be considered as CT, but again may not achieve required CA's core principles.

The CA definition proposed in this paper agrees with the one adopted by FAO (2014), Kassam et al. (2012), and Dumanski et al. (2006). As well, the definition agrees with the European Conservation Agriculture Federation (ECAF), which extended CA systems to perennial crops (ECAF, 2012).

Table II-3. Comparison of different agricultural practices concerning their environmental impact.

		Degree of environmental benefits for different environmental topics						
		Erosion /Runoff	Organic Matter increase	Compaction	CO_2 Emissions	Decrease in biodiversity	Pollution of surface water	Pollution by pesticides
Arable Crops	**TT***	-	+	++	-	-	-	-
	RT	+	+	++	++	++	++	++
	NT	++++	++++	++++	+++++	+++	+++	+++
	NT+GC	+++++	+++++	+++++	+++++	+++++	+++++	+++++
Perennial Crops	**Slight GC 30%**	++	++	++	++	++	++	++
	Average GC 60%	+++	+++	+++	+++	+++	+++	+++
	Total GC 90%	+++++	++++	+++++	+++++	+++++	+++++	+++++

TT, traditional or conventional tillage; GC, groundcovers; NT, no tillage; RT, reduced tillage; GC30%, cover crop in-between tree rows with 30% of the surface without trees; GC60%, identical to GC30% but with 60% of the surface without trees; GC 90%, identical to GC30% but with 90% of the surface without trees.

Grading of the environmental effect: + slightly positive; +++++ strongly positive; - indifferent or negative.

The beneficial effects of CA on the environment have been widely studied and disseminated by the scientific community since decades. Particularly with regard to erosion (McGregoret al.,1990; Bakeret et al., 2002; Espejo-Perez et al., 2013); increased organic matter content (Ordóñez Fernández et al., 2007a; González-

Sánchez et al., 2012; Repullo-Ruiberriz de Torres et al., 2012); improved water infiltration (Thierfelder and Wall, 2009); water usage (Blanco-Canqui and Lal, 2007); water quality (Jordan and Hutcheon, 1997); reduced water pollution (Fawcett,1995); biodiversity enhancements (López-Fando and Bello-Pérez, 1997; Kladivko, 2001); reduced CO_2 emissions (Lal, 2005; Carbonell-Bojollo et al., 2011). Likewise, several studies demonstrate the technical viability of CA in terms of yields when compared to TT (Cantero-Martinez et al., 2003; Van Den Putte et al., 2010) and also regarding the economical revenue for farmers (Uri et al., 1999; García-Torres et al., 2003). In Europe, the necessity of changing the dominant agricultural model due to problems caused by soil degradation is a need (Bakker et al., 2007; Van-Camp, 2004), so the above mentioned benefits, scientifically supported, would serve to substantiate initiatives by the Public Sector in favor of CA in the European programming period for 2014–2020. Aiming to assess environmental performance of several agricultural practices, Table II-3 compares different soil management systems for arable and perennial crops.

II-4.2. No tillage

The definition proposed is in line with national and international literature. According to studies in Spain (Ordóñez Fernández et al., 2007b), the threshold of 30% of plant residues necessary to effectively protect the soil is in agreement with the CTIC (2014). As well, NT definition is in agreement with the synonyms given in Table II-2, frequently used in the literature (Derpsch et al., 2014). ECAF referred to NT as direct sowing in its first publication (ECAF, 1999), while Baker et al. (2002) used direct drilling as a common synonym of NT, as well as Russell et al. (1975) did. Another similar term is direct seeding, often used synonymously with NT in the literature. As well, zero tillage or zero till (ZT) has been used for decades. Monneveux et al. (2006) stated that soil preparation in ZT is minimal, only enough to bury the seed.

II-4.3. Reduced tillage

The definition proposed is in agreement with CTIC (1994). The challenge of farming RT within CA resides in accomplishing the principle of leaving at least 30% of crop residues over the soil after seeding. In fact, the negative effects that the runs of machinery have on plant residues over the soil makes it very difficult to achieve that percentage of cover (Sloneker and Moldenhauer 1977; Hanna et al., 1995; Liu et al., 2010). Authors agree with Hobbs et al. (2008) and do not consider RT adequate for CA. CTIC (1994) defined RT as an agricultural practice that, by reducing tillage, could fulfil the requirements of CT depending on several factors. Baker et al. (2002) considered RT as a CT technique.

Consequently, RT does not always meet the requirements of CT. The reduction of tillage derived from RT must be accompanied by the presence of 30% of plant residues on the surface after planting. CTIC (1994) sets a percentage of plant residues present in the field after planting under RT principles of 15–30%, so in some cases it may fulfil requirements but not always. Tillage operations are cumulative in terms of the loss of plant residues at the surface, which makes it difficult to meet the requirement of maintaining surface residues (Colvin et al., 1986; Liu et at., 2010). Studies by López et al. (2003) showed that primary tillage operations had a major influence on residue incorporation, reducing the percentage of residue cover by 90–100% in TT (mouldboard ploughing), 50–70% in RT (chiseling). Two final passes of cultivator, needed in a RT routine for prepare the seedbed may leave 30–50% of residue cover. Therefore, RT seldom meet CT soil cover requirement. This is in accordance with the STIR index, which shows values not compatible with proper soil conservation when RT equipment is used.

II-4.4. Groundcovers

GC definition proposed is in accordance with Pastor et al. (2001) and García-Torres (2001). GC and cover crops have a certain language connection in Spanish, thus it is needed to distinguish among them. The reason for clarification is that cover crops have been translated into Spanish with two different terms, "cubiertas vegetales" and “cultivos cubierta”. That duplicity has created confusion for farmers, technicians and policy makers, as the First term is usable for perennial crops and the second is understood for arable crops.

Cover crops (“cultivos cubierta”) are planted in between two main arable crops, and are only a tool used for agronomic and environmental purposes, such as covering the ground, protecting nutrients from lixiviation (catch crop) or suppressing weeds (Varela et al., 2014). They can be established in both arable crops, between 2 main crops, or in the interrow of perennials. For perennial crops, those covers are translated as “cubiertas vegetales” in Spanish and not as “cultivos cubierta”. Covers comprising spontaneous vegetation, green or dry, or residues, such as prunings, are understood as well as “cubiertas vegetales” in Spanish. To avoid terminological confusion between the covers in herbaceous and perennial crops, the authors recommend the use of GC for perennial crops and cover crops for arable.

II-5. CONCLUSIONS

CA has a clear positive adoption trend in Spain, both in arable and perennial crops. Certainly, there is still a significant potential of growth, as only 7.5% of arable crops are under NT nowadays.

The definitions proposed clarify which practices fit into CA and which not, in accordance with the literature. NT is the best practice for arable crops while GC are the best approach to perennial crops. Although RT is sometimes accepted as a CT practice for arable crops, it is not considered adequate for CA.

Due to improved ecosystem services when compared to TT, CA should be broadly addressed by the Spanish Government and its Autonomous Communities in the financial framework 2014–2020.

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Chapter III.

Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture

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Chapter III. Meta-analysis on atmospheric carbon capture in Spain through the use of conservation agriculture

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III-ABSTRACT

Conservation agriculture (CA) helps to mitigate climate change. Firstly, the modifications introduced by CA on the carbon dynamics in the soil directly result in an increase of the carbon (C) in the soil fraction. Secondly, CA drastically reduces C oxidation processes by diminishing the mechanical manipulation of the soil.

Spain's position in relation to the Kyoto Protocol must be improved, as is one of the European countries in a non-compliance situation. With the aim of providing knowledge about the potential of CA as C sink in Spain, 29 articles on this subject were reviewed. According to 2010 CA uptake, the results demonstrated that conservation practices have the potential to promote the fixation in soil of about 2 Gg year^{-1} more C than traditional tillage (TT) systems. As indicated by Tebrügge (2001), 3.7 Mg CO_2 are generated from 1 Mg C through microbial oxidation processes taking place in the ground, meaning that through CA almost 7.5 Gg CO_2 could be sequestered from the atmosphere every year until the equilibrium is reached.

C fixation was found to be irregular over time. C fixation rates were high in newly implemented systems during the first 10 years, reaching top values of 0.85 Mg ha^{-1} year^{-1} for no-tillage (NT) and 1.54 Mg ha^{-1} year^{-1} for cover crops (CC) implemented in-between perennial tree rows. After those first 10 years, it followed a period of lower but steady growth until equilibrium was reached. Nevertheless, C decreases of 0.16 Mg ha^{-1} year^{-1} in the first 10 years may be expected when practicing minimum tillage (MT). C sequestration rate resulted higher in case farmers do crop rotations in NT and MT rather than monoculture. In woody crops, studies reported higher C fixation values for native species when compared to sowed CC. Also, climate conditions seem to affect C sequestration rate in Spain. Although in NT differences observed between maritime and continental climates are not pronounced, as approximately 25% of the values recorded in both climates are equal, in the case of MT about 75% of maritime climate values result higher than the continental situation.

Keywords: carbon sink, climate change, fixation coefficients, no-tillage, minimum tillage, cover crops.

III-1. INTRODUCTION

The consequences of the effects of climate change resulting from the uncontrolled emission of greenhouse gases (GHGs) and additional pressure from the international scientific community has required most countries to adopt an international agreement to implement a series of commitments to be fulfilled by the cooperating countries. These commitments, included in the so-called "Kyoto Protocol," establish a limit for the net GHG emissions based on the economic, scientific and technological development of each country (United Nations, 2011). Analysis of the major GHG types indicates that carbon dioxide (CO_2) is the dominant component in terms of absolute weight, generally above 80% overall. In a breakdown by activity sectors, in 2009 agriculture emitted 10.5% GHGs overall. The Kyoto Protocol provides several mechanisms to try to reduce GHGs, among them is the promotion of activities with a C sink effect as a solution to reduce CO_2 concentrations (West and Post, 2002).

The sink effect is any process that can fix atmospheric C. Agriculture and forestry are virtually the only activities that can achieve this effect through photosynthesis and the C incorporation into carbohydrates. Crops capture CO_2 from the atmosphere during photosynthesis by converting C forms associated with soil organic matter (SOM) for microbial decomposition processes (Johnson et al., 2007). Although agriculture is sometimes excluded from environmental regulations, its ability to offset the emissions of GHGs identifies some agricultural activities as key partner in climate policies (Claassen and Morehart, 2009).

Soil management is one of the best tools for climate change mitigation and adaptation (Lal et al., 2011). In fact, agricultural soils occupy about 35% of the global land surface (Betts et al., 2007). CA introduces important changes in the dynamics of soil C sequestration and promotes this process as well (Carbonell-Bojollo et al., 2011). Crop residues left on the soil surface and no mechanical soil disturbance reduce the rate of mulch decomposition and decrease the mineralization of SOM due to reduced air flow, resulting in a lower accessibility of microorganisms and increased soil C. Therefore, the reduction of tillage reduces and slows the decomposition of plant matter, which promotes the storage of CO_2 fixed in the plant as C and returned to the soil as plant debris. Thus, soils have the potential of storing CO_2, thereby helping to mitigate the emission of GHGs generated by other activities (Reeves, 1997). Generally, there are major differences in organic matter (OM) content between NT, CA best agri-environmental approach for arable land, and TT (Paustian et al., 1997). Hence, CA is an alternative that can help reduce GHGs, mainly due to that C-fixation in the soil through an increase of the OM (Nelson et al., 2009) and to the decrease in the intensity of tillage (FAO, 2011).

Spain, as a signatory of the Protocol, has committed to limiting the average annual net emissions of GHGs to a level of a 15% increase over the net emissions recorded in the base year (1990) during 2008–2012. Data presented at the Fifth National Communication of Spain to the UN Framework Convention on Climate Change, published in December 2009 by the Secretariat General for the Prevention of Pollution and Climate Change of the Ministry of Environment, Rural and Marine Affairs (MERMA), showed that the total emissions in 2007 were 53% over the base-year value. CA is recognized as a C sink by the MERMA and the Spanish Office for Climate Change. Indeed, reduced tillage intensity, increased arable hectares under CA, especially NT, and the use of CC were suggested for the establishment of the CO_2 absorption potential throughout Spanish territories.

Reduced tillage trials were started in Spain at the beginning of the eighties with the purpose of introducing simple conservation methods for soil, keeping a protective cover to mitigate erosion stresses, and to save water. Later, farmers detected the advantage of their reduced production costs (González Sánchez et al., 2010) and several research groups conducted studies to evaluate the benefits of CA systems on the fixation of C.

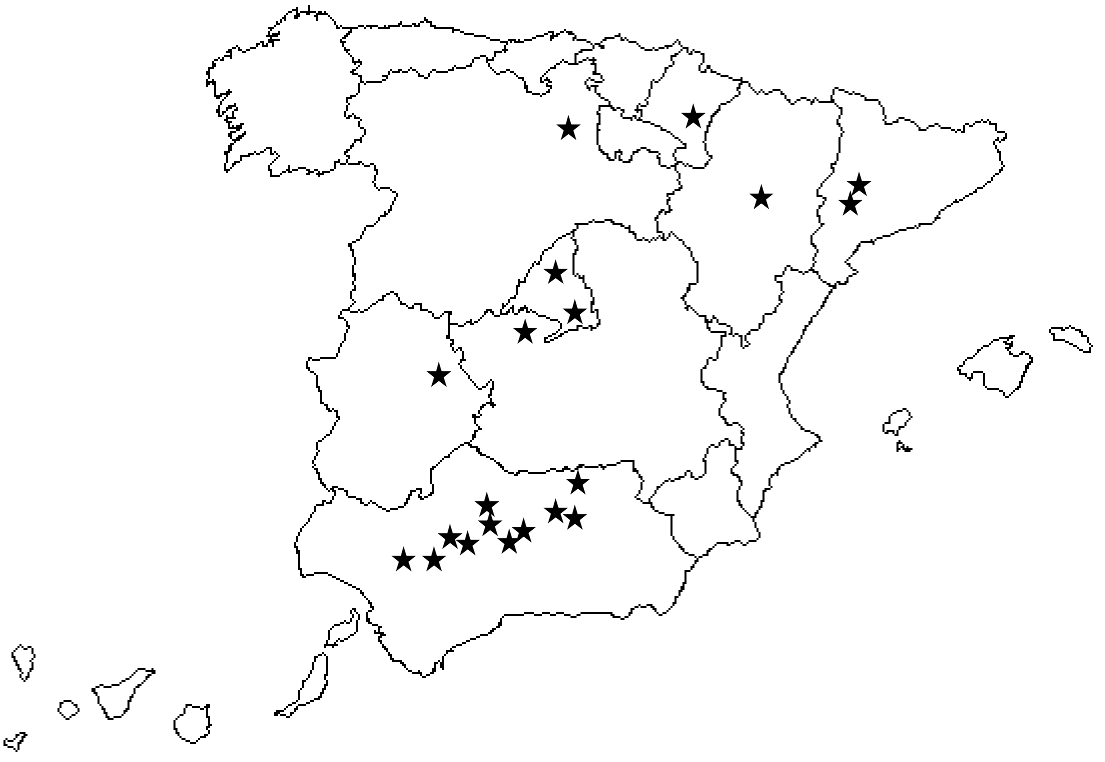

Figure III-1. Map of Spain. Stars represent areas where the studies were carried out.

As the Spanish National Plan for the Allocation of GHG Emissions Rights assumes that emissions may be reduced by 2% due to C sinks, the purpose of the present study is to provide knowledge with a solid scientific base on the potential of CA in Spain in addressing the task of reducing the concentration of CO_2 in the atmosphere through C sequestration by the review of the published works on this subject by different research groups in the Spanish Autonomous Communities of Andalusia, Aragon, Catalonia, Castille-La Mancha, Castille and Leon, Extremadura, Madrid and Navarra (Fig. III-1).

III-2. MATERIALS AND METHODS

For this study, 29 research papers were reviewed, from 20 locations, covering 11 research group papers from various areas of Spain, as listed in Table III-1. According to the literature review, the potential for C sequestration in a particular CA practice is not always equal and depends on several factors. Therefore, this study considered the following characteristics:

- Climate of the area;
- Soil type;
- Crop rotation in arable crops.

In many cases the initial values obtained were not directly comparable. Hence, certain simplifications were made in some variables to calculate a single coefficient for each CA practice. These simplifications are described below.

III-2.1. Time variable

Several studies have suggested that the soil organic carbon (SOC) content increases rapidly during the first 10 years after the change from TT to CA. After this period, the increases slow until near zero growth in the OM content is reached, indicating soil equilibrium (Yang and Wander, 1999; Puget and Lal, 2005). Consequently, coefficients given for the calculation of the potential fixation of the atmospheric C refer to two time periods. One coefficient is valid for those techniques whose implementation period does not exceed 10 years, and an additional coefficient will apply to those whose implementation period exceeds 10 years

Table III-1. List of locations and soil management systems compared.

Region	Province	Location	Soil classification	Soil management system
Andalusia	Seville	Coria del Rio	Xerofluvent	MT vs. TT
	Seville	Carmona	Chromic Haploxerept	NT vs. TT MT vs. TT
	Cordoba	Castro del Rio	Calcic Haploxerept	CC vs. TT
	Cordoba	Obejo	Ruptic–Lhitic Xerorthent	CC vs. TT
	Cordoba	Nueva Carteya	Calcic Haploxerept	CC vs. TT
	Huelva	Chucena	Typic Haploxerept	CC vs. TT
	Seville	La Campana	Typic Calcexerept	CC vs. TT
	Jaen	Torredonjimeno	Calcic Haploxerept	CC vs. TT
	Jaen	Torredelcampo	Calcic Haploxerept	CC vs. TT
	Cordoba	Cordoba	Vertisol	CC vs. TT
	Jaen	Arquillos	Anthropic Xerortent	CC vs. TT
Extremadura	Caceres	Madrigalejo	Ultic Haploxeralf	NT vs. TT
Castille-La Mancha	Toledo	Santa Olalla	Calcic Haploxeralf	NT vs. TT MT vs. TT
Madrid	Madrid	Aranjuez	Vertic Haploxeralf	NT vs. TT MT vs. TT
	Madrid	Alcala de Henares	Calcic Haploxeralf	NT vs. TT MT vs. TT
Castille and Leon	Burgos	Torrepadierne	Typic Calcixerols	NT vs. TT MT vs. TT
Aragon	Zaragoza	Penaflor	Xerollic Calciorthid	NT vs. TT MT vs. TT
Catalonia	Lleida	Selvanera	Typic Xerofluvent	NT vs. TT MT vs. TT
	Lleida	Agramunt	Fluventic Xerocrept	NT vs. TT MT vs. TT
Navarra	Navarra	Olite	Calcic Haploxerept	NT vs. TT MT vs. TT

Classified according to Soil Taxonomy (Soil Survey Staff, 1999).

CC= cover crop; MT= minimum tillage; NT= no tillage; TT= traditional tillage.

III-2.1. Time variable

Several studies have suggested that the soil organic carbon (SOC) content increases rapidly during the first 10 years after the change from TT to CA. After this period, the increases slow until near zero growth in the OM content is reached, indicating soil equilibrium (Yang and Wander, 1999; Puget and Lal, 2005). Consequently, coefficients given for the calculation of the potential fixation of the atmospheric C refer to two time periods. One coefficient is valid for those techniques whose implementation period does not exceed 10 years, and an additional coefficient will apply to those whose implementation period exceeds 10 years.

III-2.2. Depth of study variable

The potential fixation values associated with each type of CA refer to the greatest depth at which the SOM study was performed, with depths ranging from 40 to 52 cm in the cases of NT and MT and 25 to 30 cm in the case of CC. There were also two CA implementation periods studied: less than 10 years and over 10 years.

III-2.3. Study area variable

The studies reviewed in this paper represent areas with different soil and climates, indicating that the C fixing potential for the same agricultural practices would vary considerably from one case to another, making it risky to assign the whole country a single rate of C sequestration. Thus, starting from the major climatic zones in Spain, we grouped the coefficient calculations into the following two areas based on the location of the soils studied in each work:

- Areas with a continental Mediterranean climate, including Extremadura, Castille-La Mancha, Castille and Leon, Navarra, Madrid, and Aragon.

  This kind of climate affects most of the Iberian Peninsula. The climate of these areas is characterized by significant differences in temperature between day and night and the different seasons of the year. It has two rainy seasons, in autumn and spring, with annual averages between 300 mm and 500 mm. There are very hot summers with high temperatures, and cold winters with frequent frosts. Summer temperatures have important variations between day and night, ranging from 30° C - 40° C in the day to 10° C at night.

- Areas with a maritime Mediterranean climate, comprising Andalusia and Catalonia.

  The maritime area is characterized by mild winters, long dry summers and rainy autumns and springs. The average winter temperatures along the coast about 10–13° C, while inland of Andalusia are a few degrees lower. In summer average temperatures are around 22–27° C along the coast and often exceed 40° C in the Andalusian inland. Average rains are between 400 and 600 mm.

III-2.4. How to calculate the C fixation coefficient

The analysis of the C sink effect of CA was performed through a literature review of existing research in Spain through the year 2009, in studying the effects various soil management systems have had on the OM content over different periods. These systems included NT and MT in arable crops and in woody crops the use of CC. To estimate the potential of CA for C sequestration, in each study, the increase of observed OM in the conservation management systems was evaluated in relation to TT. For each soil depth interval studied *i*, C increases are proposed in terms of quantities of C from the organic carbon (OC) in the soil, according to the following formulae:

$$OC_i(kg/ha) = OC_i(kg_{OC}/100\,kg_{soil}) \times \rho_i(kg_{soil}/m^3) \times D_i(m) \times 10^4\,m^2/ha \qquad (1)$$

$$OC_i(Mg/ha) = 10^{-3}\,OC_i(kg/ha) \qquad (2)$$

where ρ_i is the bulk soil density and D_i is the depth of the interval studied.

Total C content is determined for the studied total depth *Dt*, making the sum of the amounts obtained for each soil depth interval sampled, as follows:

$$OC_{Dt}TT(Mg/ha) = \sum_{1}^{n} OC_i TT \qquad (3)$$

$$OC_{Dt}CA(Mg/ha) = \sum_{1}^{n} OC_i CA \qquad (4)$$

where *n* is the total number of depth intervals studied in the experience being analyzed. This number of intervals varies from one study to another as each author decides the total depth to sample. Thus, in a determinate reviewed study *j*, the average annual increase in C stored in soils under CA compared to TT soil to the total studied depth D_{tj}, after Y_j years of experience is obtained as follows:

$$\Delta OC_{Dtj}(Mg/ha\ year) = \left(\mathrm{OC}_{\mathrm{Dtj}}\ \mathrm{CA(Mg/ha)}\ -\ \mathrm{OC}_{\mathrm{Dtj}}\ \mathrm{TT(Mg/ha)}\right)/Y_j \qquad (5)$$

where ΔOC_{Dtj} is the C annual fixation coefficient for the reviewed study *j*.

For each climatic zone there are two groups, on one side those works whose term of study is less than 10 years and on the other, those exceeding 10 years of experimentation. On this basis, for each climatic zone and duration of the study, a matrix associates increases in OC for the different total depths D_t of each study *j* reviewed. The calculation of the annual average C fixation rate, *FC*, comes from the weighted average of these increases, taking into account the maximum depth of study in each area and time period considered, as follows:

$$FC(Mg/ha\ year) = \sum_{j=1}^{j=S} \Delta OC_{Dtj} x\left(D_{tj}/D_{t\max}\right) \Big/ S \qquad (6)$$

where:

FC = annual average C fixation coefficient.

Dt_{max} = Maximum total sampling depth of all studies corresponding to the climatic zone and time period considered.

S = Total number of studies corresponding to the climatic zone and time period considered.

III-3. RESULTS AND DISCUSSION

In recent years, the OC pool in cultivated land and the practices that contribute to its increase have been widely studied because of the potential influence on the reduction of CO_2 (Schlesinger, 2000). Contents of SOC are influenced either directly or indirectly by human activities (Fantappiè et al., 2010; Farina et al., 2011; Hernanz Martos et al., 2009) but also in an important way, that storage volume is affected by soil variability of the farm, physic-chemical characteristics of soil and environmental conditions affecting the absorption and release of C.

Changes in land management systems directly affect soil C content (Guo and Gifford, 2002). A C cycle modeling study has shown that changes in soil management have a greater impact on the soil C content than predicted by climate change (Smith et al., 2005). The results presented by authors may be quite different depending on the area where is carried out the study, due to the importance of climate in the C cycle. Other factors that influence and may differentiate the results are the depth of the profile considered in the study and the crop rotations.

According to Paustian et al. (1997), the increasing in OM levels that result under CA depends on the soil management system and other factors that are involved, such as the soil climatic conditions (temperature and humidity), the biochemical composition of the organic material, the nutrient availability and the level of soil disturbance. There is great variability in the potential of these techniques to fix C; thus, there is no single value of C sequestration that applies to a particular CA practice. In addition, based on the observations reported in these research studies, the increases that occur are not constant over time: at the beginning of the experiment, the SOM growth rate is high and decreases over time to achieve an eventual equilibrated rate of zero growth.

The results of our study confirm those reported by other authors on the idea that the amount of C that can store a soil is not unlimited. Experiments have shown how the increases are higher just after a change in use or land management and decrease over time to approach a new steady state (Freibauer et al., 2004). From that moment it is said that the storage capacity of the soil is saturated (IPCC, 2000). In a long-term study in two olive farms with soils classified as Calcic Vertisol and Chromic Calcisol, Nieto et al. (2010) reported annual increases in C concentration of 25.3 Mg ha^{-1} and 23.6 Mg ha^{-1} respectively at 6 and 5 years of installation of a pruning cover. After that, decreases to 1 Mg ha^{-1} year^{-1} are to be considered in a whole period of 26 years. Accordingly, those works in which are presented results of studies for a period of time exceeding 10 years, will be more representative of the evaluated area.

Another aspect to consider is the unequal distribution in the profile of the SOC for TT and CA. The overall view of all studies reviewed indicates that the C fixation data provided by those experiences which provides a greater volume of soil will be more reliable when making the comparison between different systems evaluated in the study. According Franzluebbers (2000), stratification of SOC calculated as the ratio of the concentration in the surface layer from a deeper, can be used as C fixation index to compare different soil management systems.

III-3.1. Coefficients of C fixation for NT

Tables III-2 and III-3 show the C increase for NT compared to TT, for different climatic zones. Articles reviewed demonstrate that NT stimulates soil C sequestration. Indeed, NT is the practice included in CA with a higher level of soil conservation for arable crops, where the absence of tillage favors C sequestration. In NT, the OC increase is evident in the surface soil layer. Ismail et al. (1994) reported significant changes in the upper 5 cm of the soil profile. In-depth effect of NT has not been observed in other studies, Rhoton (2000) constrained the positive effect of NT only in the top 2.5 cm layer. Ordóñez-Fernández et al. (2007), reported substantial differences in the OC content in the first 13 cm, with an increase of 23% in comparison to TT. The growing trend was maintained for a longer period than the 4 years observed by Rhoton et al. (2002), as SOC was still improving after 20 years.

Table III-2. List of studies referred and C-fixation rates of no tillage for the continental Mediterranean climate zone.

	Study period (years)	Maximum soil depth sampled (cm)	Increase over traditional tillage C (Mg ha^{-1} year^{-1})	Type of crop[a]
EX1 (Muñoz et al., 2005)	5	30	0.61	Monoculture of maize
EX2 (Muñoz et al., 2007)	5	30	0.71	Monoculture of maize
CM1 (Lacasta and Meco, 2005)	9	20	1.00	Monoculture of barley
CM2 (López-Fando et al., 1995)	2	20	1.79	Monoculture of barley
CM3 (López-Fando et al., 2001)	12	30	0.02	Monoculture of barley
CM2 (López-Fando et al., 1995)	2	20	1.73	Barley-vetch
CM3 (López-Fando et al., 2001)	12	30	0.10	Barley-vetch
CM2 (López-Fando et al., 1995)	2	20	2.12	Barley-sunflower
CM3 (López-Fando et al., 2001)	12	30	0.09	Barley-sunflower
CM4 (López-Fando et al., 2005, 2007)	10	30	0.40	Barley-pea
MA1 (AEAC.SV, 2006)	7	40	1.69	Wheat-maize
MA1 (AEAC.SV, 2006)	7	40	2.01	Fallow-barley-Legume
MA2 (Hernanz et al., 2002)	11	40	0.16	Monoculture of Cereal
MA2 (Hernanz et al., 2002)	11	40	0.21	Wheat-vetch
MA3 (Hernanz et al., 2005)	19	40	0.36	Wheat-vetch
MA4 (Hernanz et al., 2009)	20	40	0.41	Wheat-vetch
CL1 (De Benito and Sombrero, 2006)	10	30	0.24	Wheat-vetch
AR1 (Álvaro et al., 2004)	15	5	0.13	Monoculture of barley
AR1 (Álvaro et al., 2004)	15	5	0.12	Barley-vetch
NA1 (Bescansa et al., 2006)	12	30	0.56	Monoculture of barley
Mean			0.72	
SE Mean ($p < 0.05$)			0.16	

EX= Extremadura; CM= Castille-La Mancha; MA= Madrid; CL= Castille and Leon; AR= Aragon; NA= Navarra.

[a] Scientific names: barley= *Hordeum vulgare* L.; maize= *Zea mays* L.; pea= *Pisum sativum* L.; sunflower= *Helianthus annuus L.;* vetch= *Vicia sativa* L.; wheat= *Triticum* L.

Table III-3. List of studies referred and C-fixation rates of no tillage for the maritime Mediterranean climate zone.

Study	Study period (years)	Maximum soil depth sampled (cm)	Increase over traditional tillage C (Mg ha^{-1} $year^{-1}$)	Type of crop[b]
AN6 (Ordóñez et al., 1997)	11	52	0.96	Wheat-sunflower-Legume
AN7 (Ordóñez et al., 2007)	19	52	0.47	Wheat-sunflower-Legume
CA1 (Álvaro-Fuentes et al., 2006)	18	5	0.16	Monoculture of barley
CA2 (Álvaro-Fuentes et al., 2007)	18	20	0.25	Monoculture of barley
CA1 (Álvaro-Fuentes et al., 2006)	18	5	0.11	Barley-fallow
CA2 (Álvaro-Fuentes et al., 2007)	18	20	0.15	Barley-fallow
CA1.1 (Álvaro-Fuentes et al., 2006)	15	5	0.08	Cereal-rape
CA2.1 (Álvaro-Fuentes et al., 2007)	15	20	0.05	Cereal-rape
CA1.2 (Álvaro-Fuentes et al., 2006)	15	5	0.25	Cereal-rape
CA2.2 (Álvaro-Fuentes et al., 2007)	15	20	0.38	Cereal-rape
Mean			0.29	
SE Mean ($p < 0.05$)			0.09	

AN= Andalusia, CA1.1= Catalonia, Selvanera farm; CA1.2= Catalonia, Agramunt farm

[b] Scientific names: barley= *Hordeum vulgare* L.; rape= *Brassica napus* L.; sunflower= *Helianthus annuus L.;* wheat= *Triticum* L

In the Andalusian countryside, after 21 years of trials, Ordóñez-Fernández et al. (2007) have reported an increase of 18 Mg ha^{-1} in the OC content under NT of a wheat (*Triticum aestivum* L. and *Triticum durum* Desf.), sunflower (*Helianthus annuus* L.) and legume plants, broad beans (*Vicia faba* L.), chickpea (*Cicer arietinum* L.), vetch (*Vicia sativa* L.), and pea (*Pisum sativum* L.) rotation, whereas TT did not result in any increase. However, the differences between the tillage systems disappeared with depth, showing more OC under TT beyond 25 cm. In an experiment in semi-arid conditions in Navarra, Bescansa et al. (2006) have reported a significantly higher OM content in the first 15 cm of soil under NT systems, compared to TT. López-Fando et al. (2007) have observed significant differences in the amount of C stored in the top 10 cm of untilled soils, compared with those traditionally managed, but there was no significant difference at greater depths. These results are similar to those reported by Aguilera et al. (1996) where authors evaluated the OC and bioactivity in an Andisol soils.

Martino (2001) has shown that the NT system is one of the main mechanisms by which C is sequestered in agriculture. However, the sequestration increases until it reaches a new equilibrium for the system used (20 or more years). Changes in soil management practices require time to detect variations in the soil organic carbon (SOC), adding some difficulties to evaluate short-term field experiments (Álvarez and Álvarez, 2000). Furthermore, the short-term (<10 years) effects of management on the SOC are complex and vary with soil conditions, such as the soil texture, climate, cropping system and kind of crop residue, as well as with the management system itself (Muñoz et al., 2007). NT practices generally increase the sequestration of C, but this increase might not be apparent for approximately 5–10 years (West and Post, 2002).

The quantity and quality of the mulch in the soil is a consequence of the alternation of the previous crops, because crop rotations produce a higher quality and quantity of dry matter than monoculture do (Copeland and Crookston, 1992). Table III-2 demonstrates, in general, that higher soil fixation values are found in soils in which crops are rotated. These results are consistent with those reported by Martino (2001), who had observed over a 30-year study that the soil under a rotation of crops and pastures had between 15 and 20 Mg of C per ha more than under monoculture farming.

A statistical analysis of NT reviewed studies show that those with crop rotations obtained a C sequestration mean of 0.64 Mg ha^{-1} $year^{-1}$ ($p < 0.05$, SE mean = 0.17), while those under monoculture reached 0.54 Mg ha^{-1} $year^{-1}$ ($p < 0.05$, SE mean = 0.17). Therefore, C sequestration rate resulted about 19% higher in case farmers do crop rotation in NT rather than monoculture. Finally, if all C sequestration data is analyzed by climates, in the case of NT (Fig. III-2) differences observed between two climates are not pronounced, as approximately 25% of the values recorded in both climates are equal. However, both the median and the rest of the three headquarters are higher in the case of the maritime climate.

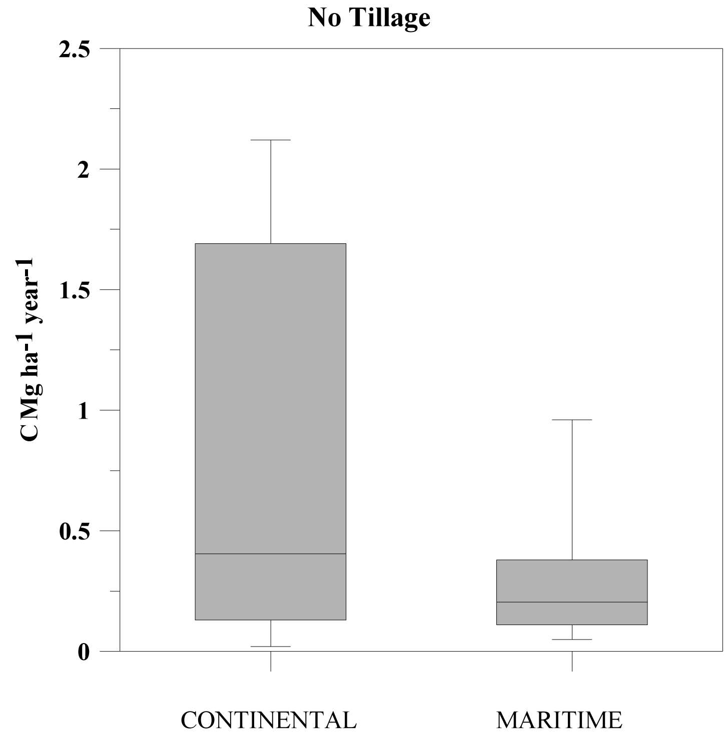

Figure III-2. C fixation in no tillage in maritime and continental Mediterranean climates.

III-3.2. Coefficients of C sequestration for MT

In Tables III-4 and III-5, the regional coefficients of C sequestration are compared, from which are calculated the standard rates of C sequestration for the practice of MT. MT is an agronomic practice with a lower conservation effect than NT, that is why results in a lower increase in the C fixation. As shown in Table III-4, compared to TT, the fixation rate is even negative in some cases.

In an experiment in the province of Seville, Moreno et al. (2006) have found a higher OC content in the first 10 cm of the soil under MT compared to a TT system. Higher fixation values were also evident in an 11-year study following the rotation of wheat-sunflower-legume where the controlled depth was 52 cm (Ordóñez-Fernández et al., 1997), whereas the worst case reported was an 11-year study on a wheat-corn rotation where the controlled depth was 40 cm (AEAC.SV, 2006) where tilled soils fixed a higher amount of C relative to those subjected to MT. In the case of MT is not very clear the influence of time, depth, and cultivation on the increase in C sequestration, compared to TT.

In the case of MT, C sequestration rate is higher in case farmers do crop rotation rather than monoculture. A statistical analysis of MT reviewed studies show that those with crop rotations obtained a C sequestration mean of 0.27 Mg ha^{-1} year^{-1} ($p < 0.05$, SE mean = 0.11), while those who carry out monoculture reached 0.04 Mg ha^{-1} year^{-1} ($p < 0.05$, SE mean = 0.16).

Table III-4. List of studies referred and coefficients of C-fixation of minimum tillage for the continental Mediterranean climate zone.

Study	Study period (years)	Maximum soil depth sampled (cm)	Increase over traditional tillage C (Mg ha-1 year-1)	Type of crop[c]
CM4 (López-Fando et al., 2005, 2007)	10	30	-0.18	Barley-pea
MA1 (AEAC.SV, 2006)	7	40	-0.50	Wheat-maize
MA2 (Hernanz et al., 2002)	11	40	-0.31	Monoculture of Cereal
MA2 (Hernanz et al., 2002)	11	40	0.17	Wheat-vetch/pea
MA3 (Hernanz et al., 2005)	19	40	-0.01	Wheat-vetch/pea
MA4 (Hernanz et al., 2009)	20	40	0.02	Wheat-vetch/pea
CL1 (De Benito et al., 2006)	10	30	0.18	Wheat-vetch/pea
AR1 (Álvaro-Fuentes et al., 2004)	15	5	-0.01	Monoculture of barley
AR1 (Álvaro-Fuentes et al., 2004	15	5	0.03	Barley-fallow
NA1 (Bescansa et al., 2006)	12	30	0.45	Monoculture of barley
Mean			-0.01	
SE Mean (p <0.05)			0.08	

CM= Castille-La Mancha; MA= Madrid; CL= Castille and Leon; AR= Aragon; NA= Navarra.

[c] Scientific names: barley= *Hordeum vulgare* L.; maize= *Zea mays* L.; pea= *Pisum sativum* L.; sunflower= *Helianthus annuus L.;* vetch= *Vicia sativa* L.; wheat= *Triticum* L.

Table III-5. List of studies consulted and coefficients of C-fixation of minimum tillage for the Mediterranean climate zone.

Study	Study period (years)	Maximum soil depth sampled (cm)	Increase over traditional tillage C (Mg ha-1 year-1)	Type of crop[d]
AN1 (Murillo et al., 1998)	6	30	0.66	Wheat-sunflower
AN2 (Moreno et al., 2005)	11	25	0.60	Wheat-sunflower
AN3 (Moreno et al., 2006)	11	25	0.54	Wheat-sunflower
AN4 (Murillo et al., 2006)	13	25	0.27	Wheat-sunflower
AN5 (Madejón et al., 2007)	14	25	0.72	Wheat-sunflower
AN6 (Ordóñez et al., 1997)	11	52	0.77	Wheat-sunflower-Legume
CA2 (Álvaro-Fuentes et al., 2007)	18	20	0.02	Monoculture of barley
CA2 (Álvaro-Fuentes et al., 2007)	18	20	0.08	Barley-fallow
CA2 (Álvaro-Fuentes et al., 2007)	15	20	0.22	Wheat-barley
Mean			0.43	
SE Mean (p <0.05)			0.10	

AN= Andalusia, CA= Catalonia.

[d] Scientific names: barley: Hordeum vulgare L.; sunflower: Helianthus annuus L.; wheat: Triticum L.

If all C sequestration data is analyzed by climates, in the case of MT (Fig. III-3) differences observed between two climates are very pronounced. In the maritime climate almost all registered values are higher than 75% of the values that have occurred in the case of the continental climate and the value of its median is close to their maximum observed in the continental climate.

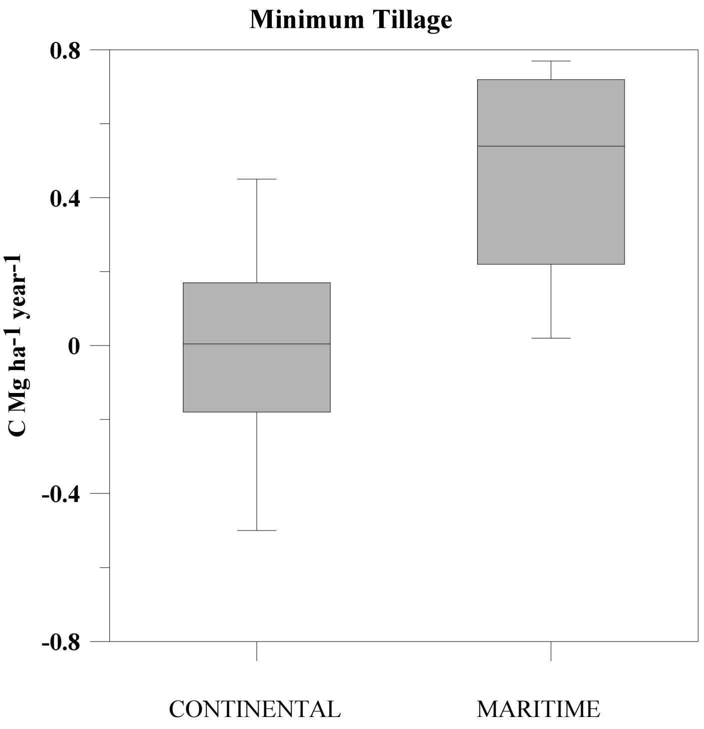

Figure III-3. C fixation in minimum tillage in maritime and continental Mediterranean climates.

III-3.3. Coefficients of C sequestration for CC

The benefits reported in the literature related to CC are very broad and include the reduction of surface water pollution (Rodríguez-Lizana et al., 2007), the improvement of the balance of water in the soil (Bowman and Bilbrough, 2001), the aid in the control of weeds (Hatcher and Melander, 2003), and the recycling of unused soil N (Weiner et al., 2002). However, C fixation rates are favored by not tilling the soil under CA with woody crops and the ability of CC to capture CO_2 and deliver C to the soil as during decomposition, when compared with TT. In Table III-6, the coefficients of CO_2 are listed by region, from there were calculated the standard rates for the use of CC.

The C storage capacity of a soil depends on its characteristics and the weather, which is a reason for the high variability in the values for fixation in the various studies reviewed. However, more important than the sampling depth is the time to control the test CC that has given the major difference between management systems.

Furthermore, CC using native grass generally gave higher rates of C fixation (Table III-6).

Table III-6. List of studies cited and coefficients of C-fixation for cover crops.

Study	Study period (years)	Depth (cm)	Increase over traditional tillage C (Mg ha-1 year-1)	Location	Type of cover crop[e]
AN9 (Márquez et al., 2008)	4	25	0.41	Cordoba (Castro del Río)	Native species
AN9 (Márquez et al., 2008)	4	25	4.64	Cordoba (Nueva Carteya)	Native species
AN9 (Márquez et al., 2008)	4	25	3.11	Cordoba (Obejo)	Native species
AN10 (Gómez et al., 2004)	4	5	0.28	Cordoba	Barley
AN11 (Gómez et al., 2009)	4	10	0.35	Cordoba	Barley
AN9 (Márquez et al., 2008)	4	25	2.26	Jaen (Torredonjimeno)	Ryegrass
AN9 (Márquez et al., 2008)	4	25	1.75	Jaen (Torredelcampo)	Ryegrass
AN12 (Castro et al., 2008)	28	30	0.11	Jaen (Arquillos)	Native species (chemical mowing)
AN12 (Castro et al., 2008)	28	30	0.27	Jaen (Arquillos)	Native species (mechanical mowing, brush cutter)
AN12 (Castro et al., 2008)	28	30	0.69	Jaen (Arquillos)	Native species (mechanical mowing, brush cutter + cultivator)
AN9 (Márquez et al., 2008)	4	25	1.88	Sevilla (La Campana)	Native species
AN9 (Márquez et al., 2008)	4	25	1.79	Huelva (Chucena)	Native species
AN9 (Márquez et al., 2008)	4	25	3.08	Huelva (Chucena)	Native species
Mean			1.59		
SE Mean (p <0.05)			0.39		

AN= Andalusia.

[e] Scientific names: barley= Hordeum vulgare L.; ryegrass= Lolium L.; wheat= Triticum L.

A statistical analysis of CC reviewed studies show that those with native species obtained a C sequestration mean of 1.78 Mg ha^{-1} year^{-1} ($p < 0.05$, SE mean = 0.52), while those with sowed species reached 1.16 Mg ha^{-1} year^{-1} ($p < 0.05$, SE mean = 0.50).

III-3.4. Average potential CO_2 fixation based on the soil surface under CA in Spain

An evaluation of the estimated coefficients was performed and represents the reduction of GHG emissions in Spain, taking into account the percentage of arable land occupied by crops under CA.

In this regard, the official data available in Spain for the case of NT and CC are presented in the Survey Areas and Crop Yields, from the MERMA (2009, 2010). In the case of MT, the estimates by the Spanish Association for Conservation Agriculture Living Soils (AEAC.SV, 2011) suggested an adoption by farmer figure for 2009 of 1.3 M ha and 1.5 M ha for 2010.

The MERMA data for NT and CC, together with the estimates by the AEAC.SV for the MT for the 2009 and 2010 seasons are presented in Table III-7.

Table III-7. Area under conservation agriculture in Spain.

	Woody crops (2010)	%	Woody crops (2009)	%
Total (ha)	4,986,046	100	5,043,896	100
CC (ha)	1,218,726	24.4	1,066,182	21.1
	Arable crops (2010)	%	Arable crops (2009)	%
Total (ha)	7,182,050	100	7,341,709	100
NT (ha)	428,638	6.0	274,528	3.7
MT (ha)	1,500,000	20.9	1,200,000	16.3

Given these values of land use in Spain of crops under CA and the years of duration that the experiment was performed, the calculated potentials for C fixation in Spain are presented in Table III-8. Based on the research conducted and the data of agricultural area in Spain dedicated to the CA, we conclude that around 2 Gg C would be fixed per year over TT, due to the soil C sink effect promoted by CA.

Table III-8. Area cultivated in Spain under conservation agriculture (2010) and potential C fixation over traditional tillage.

Agricultural Practice	C coefficient of fixation (Mg ha-1 year-1)	Period	Area (ha)	Fixation potential of C (Mg year-1)
NT	0.85	<10 years	378,638	321,842
	0.16-0.40	>10 years	50,000	8,000-20,000
MT	-0.16	<10 years	800,000	-128,000
	0.03-0.30	>10 years	700,000	21,000-210,000
CC	1.54	<10 years	1,128,559	1,737,981
	0.35	>10 years	90,167	31,558
Total				1,992,381-2,193,381

III-4. CONCLUSIONS

CA implementation would help Spain's Government to meet the targets set in the Kyoto Protocol. The potential for C fixation in CA systems is not constant over time. Thus, in newly implemented systems, fixation rates are high during the first 10 years or so, followed by a period of lower but steady growth to reach an equilibrated rate.

Due to the influence of climatic and soil characteristics on potential C fixation, it is not advisable to report the absolute mitigation of GHGs related to CA practices, therefore potential fixation must always be described relative to TT. NT for arable crops and CC for woody crops leads to increased C sequestration in any period. In contrast, MT in the short term may lead to a slight decrease in C, although in long-term experiences favors C sequestration.

The more homogeneous the climate area, total depth sampled and crop rotation followed, the more accurate the C fixation rate would be. Crop rotations presented higher values of C fixation coefficients than monocultures in arable crops. In woody crops, native cover crop species lead to higher values of C fixation coefficients than sowed species.

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Chapter IV.

Soil management systems and short term CO_2 emissions in a clayey soil in southern Spain

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Chapter IV. Soil management systems and short term CO_2 emissions in a clayey soil in southern Spain

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IV-ABSTRACT

The soil in general and that destined for agricultural use, more specifically, can act as a source or sink of carbon, hence its direct involvement in strategies for mitigating climate change. A large proportion of this mitigation potential is produced by the sequestration of carbon by soils and, to a lesser extent, by a reduction in emissions from the soil.

The most effective practices for increasing the organic carbon in the soils are generally those linked to conservation agriculture, which includes practices of no tillage or minimum tillage and the use of cover crops. During the farming seasons of 2006/07, 2007/08, 2008/09 and 2009/10, a trial was conducted in which the carbon dioxide emissions in soil with a high percentage of clay in the Vega de Carmona (Seville) were estimated, and it was determined how climate conditions and the adoption of conservation agriculture practices vs. the use of traditional tillage influenced the flux of gas into the atmosphere.

Keywords: conventional tillage, no tillage, conservation agriculture, CO_2 emissions, soil management.

IV-1. INTRODUCTION

Organic matter (OM) is involved in the enhancement of soil quality because it acts on soil structure, nutrient storage and biological activity. It is a key soil component, as it affects the chemical, physical and biological properties of soil, and it is essential for obtaining crops with stable, high yield levels (Franzluebbers, 2002). The intensification of tillage to which European agricultural soils have been subjected since the second half of the 20th century has caused a notable diminution in soil OM content (Maljean et al., 2004). The soil organic C (SOC) present in agricultural soils represents approximately 10% of the total organic C stored in all the soils on the earth's surface (Paustian et al., 1997a). Despite this low proportion, the SOC stored in agricultural soils has had important repercussions on increases in greenhouse gas (GHG) concentrations for decades. The typically Mediterranean climate of the south of Spain promotes low crops yields and low organic carbon content in the soil.

Crops capture CO_2 from the atmosphere during photosynthesis, converting carbon into forms associated with organic matter in the soil during microbial decomposition processes (Johnson et al., 2007). Although agriculture is usually excluded from environmental regulations, its capacity to compensate for the GHG emissions coming from diverse emission sources makes it possible for agriculture to play an important role in climate policies (Claassen and Morehart, 2009).

The CO_2 concentration in the atmosphere has increased by approximately 25% in the past century. Carbon dioxide has a great heating potential, as this type of GHG presents the shortest life cycle and shows a lower infrared radiation absorption potential compared to other GHGs (U.S. Environmental Protection Agency., 2010).

Since the 17th century, the factors most responsible for the increase in CO_2 in the atmosphere have been first the decomposition of organic matter in the soil and the burning of large plant masses associated with the conversion of large areas of fields and forests into agricultural soils and second the burning of fossil fuels (Greenhouse Gas Working Group, 2010).

Throughout the 21st century, it is expected that the increased GHG concentration in the atmosphere and its consequences for the climate change will have greater impacts. These measures are included in articles 3.3 and 3.4 (IPCC, 2000). It is forecast that the increase in NO_2 emissions will reach between 35 and 60% in 2030 due to increased use of nitrogenous fertilizers (FAO, 2003). Similarly, Mosier and Kroeze (2000) and the US-EPA (2006) estimate that NO_2 emissions will be increased by 50% for the year 2020 (with respect to 1990). Additionally, CH_4 emissions are expected to increase by up to 60% by 2030 (FAO., 2003). The data related to CO_2 emissions increases for 2030 are more uncertain, but according to the US-EPA (2006), it has been estimated that during the decades 2000–2010 and 2010–2020, there will be an increase of 13%, and a similar increase (10–15%) is assumed for 2020–2030.

Conservation agriculture has introduced important changes in the dynamics of C in the soil and favors its sequestration. The combination of leaving crop residues on the soil surface and not disturbing the soil directly results in a reduction in the decomposition rate of the crop remains; a diminution in the mineralization of the soil organic matter due to less aeration and a lower accessibility of microorganisms to it; and an increase in soil carbon (Balota et al., 2004., Ordóñez Fernández et al., 2008).

It is frequently observed that the major differences in OM content between no-tillage (NT) and traditional tillage (TT) soils are found in the upper few centimeters of soil (Dick et al., 1991). Paustian et al. (1997b) compared 39 paired tillage experiments ranging in duration from 5 to 20 years and estimated that NT resulted in an average soil C increase of 285 g m^{-2} compared to TT. Using an average experiment duration of 13 years implies an approximate C sequestration rate of 22 g m^{-2} $year^{-1}$.

When soil is subjected to a type of operation that results in the alteration of its profile, such as soil disturbance or inversion, the flux of the CO_2 emissions into the atmosphere is increased. This increase begins immediately after conducting the operation and lasts for a certain period of time. This response may be due to the breaking up of aggregates, which leaves organic matter unprotected and exposed to the decomposing action of microorganisms (La Scala et al., 2008).

SOC concentrations and soil texture most likely influence aggregate stability. The magnitude of soil disturbance and the amount of residue incorporated into the soil impact aggregates and the associated C pool (Blanco-Canqui and Lal, 2004).

Thus, the type of tilling operation modifies the trend of CO_2 emissions from the soil (Sánchez et al., 2003).

Recently, studies validating this conclusion have been appearing. Based on a study on CO_2 sinks, Figueroa and Redondo (2007) indicated that according to the climatological characteristics of an area, it can be estimated that fields dedicated to agricultural crops are capable of capturing between 0.1 and 1.0 ton of carbon per ha and per year. In Spain, a number of investigations have supplied information on short-term emissions due to different types of tillage (Álvaro-Fuentes et al., 2007, López-Garrido et al., 2009).

Land use management of agricultural systems is known to change the storage of soil organic carbon through variations in land use, tillage, cropping practices and other activities. Consequently management and land use can be used to mitigate greenhouse gas emissions by encouraging practices that sequester carbon in the soil, thus creating a carbon sink for atmospheric CO_2 (Paustian et al., 1997b). Reviewing the scant literature available on this theme, it can be deduced that the effects of agricultural operations on CO_2 emissions are strongly influenced by the type of operation, soil type, and climate conditions in the area. The objective of this study was to evaluate the influence of the management system used on a vertisol in the south of Spain under a Mediterranean climate on the flux of CO_2 into the atmosphere.

IV-2. MATERIALS AND METHODS

IV-2.1. Localization of the field trial and climate conditions in the area

Our experiments were conducted in a long-term field trial established in 1982 in the Experiment Station of Tomejil in the Campiña de Carmona, Seville, Spain, with coordinates of 37° 24′ 07″N and 05° 35′ 10″W.

Data were collected in a plot of 3.5 ha in which a long-term soil management field trial has been conducted since 1982. In this plot, an evaluation was made of the effects produced by different soil management systems, including Traditional tillage (TT) and No tillage (NT), on the physical, chemical, and biological qualities of the soil, as well as the crop yields in a wheat–sunflower–legume rotation.

The soil in the study area is classified as very fine Montmorillonite, Chromic Haploxeret (Soil Survey Staff., 1999). It presents good natural fertility, with high concentrations of potassium and calcium, medium levels of phosphorus, low organic matter content and a pH tending towards neutrality. The principal component of its textural composition is clay, with values of over 60% distributed in 70% of expandable Montmorillonite type clay, 20% of illite and 10% of kaolinite (Perea, 2000). Table IV-1 shows the physicochemical characteristics of the soil.

Table IV-1. Physico-chemical characteristics of the upper 0.2 m of the soil studied under the two tillage treatments investigated.

	Texture (%)			**Chemical properties**						
	Sand %	**Lime** %	**Clay** %	**pH**	**OC** g kg^{-1}	**P** mg kg^{-1}	**K** mg kg^{-1}	**Ca** mg kg^{-1}	**Mg** mg kg^{-1}	**CEC** $mol_c kg^{-1}$
Tradicional Tillage	6.3	31.4	62.2	7.6	9.5	12.7	649.0	605.0	28.7	0.5
No Tillage	7.8	36.5	56.4	7.5	12.0	24.6	858.0	499.0	28.5	0.5

The area presents a Mediterranean-type climate, characterized by long summer droughts with a great inter-annual and intra-annual irregularity in rainfall. This variability, together with the high temperatures recorded during the summer, hinders agricultural activity to a great extent.

The mean annual rainfall ranges around 475 mm and is concentrated in the autumn and the beginning of spring, whereas a smaller amount is observed in the winter. The highest temperatures are recorded in July and August and sometimes exceed 35 °C, whereas the minimum temperatures are usually recorded in February and rarely fall below 0 °C (Perea, 2000).

The weather conditions during the trial period can be seen in Fig. IV-1.

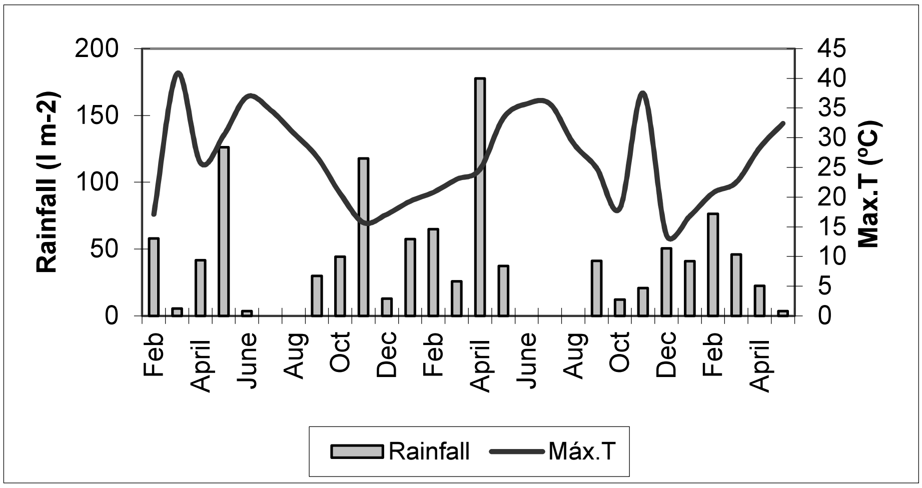


Figure IV-1. Distribution of the rainfall and maximum temperatures recorded during the period of the Carmona study.

IV-2.2. Experimental design

The tillage systems compared in the trial were traditional tillage and no tillage. TT consists of a disk plow pass after stubble is burnt and successive cultivator passes to decrease soil clod size. In the NT treatment, we used a tine seeder. The speed of seeding is very important. If it is high, the bars exert much pressure on the soil and alter its surface profile, so the soils in this treatment were seeded at a low speed of 0.6 m/s, which ensures a good distribution of seeds and causes no alteration due to pressure on the soil surface. The residue is left on the soil surface until it decays.

The depth reached in the tillage operations is a very important factor in determining the dynamics of CO$_2$ emissions, so we proceeded to make a comparison between a disk plow reading down to 20 cm of the profile, which has been the normal procedure in the study plots devoted to traditional tillage, and a moldboard plow, which reached depths up to 40 cm, in some plots adjacent to the experimental plots.

The plots were 15 m wide and 180 m long and were replicated three times in a randomized complete block design. To evaluate the temporal evolution of the flow of CO$_2$ into the atmosphere in each plot, 9 points were chosen. In addition to these, a tenth point was chosen within each plot around the central random within a radius of 1 m to take into account the spatial variability of emissions (Fig. IV-2).

This study was conducted in three consecutive farming seasons, 2006/07, 2007/08, 2008/09 and 2009/10, in which pea, wheat, sunflower and pea were grown, respectively.

IV-2.3. Emission measurements

To evaluate the temporal evolution of CO$_2$ emissions, in each of the plots, 9 points were chosen in which measurements of the CO$_2$ emissions into the atmosphere were made. In addition to these, a tenth point was selected in each random plot around the central one at a radius of approximately 1 m (Fig. IV-2).

Gas flow was estimated by means of a portable IR absolute and differential PP-Systems EGM-4 gas analyzer. This consists of a battery, integrated data recorder and soil temperature sensor and is coupled with a respiration camera. This suction or respiration camera is approximately 15 cm high and 10 cm in diameter.

The machine is calibrated automatically using the surrounding air before each measurement as a reference, and it automatically transfers the obtained data to a computer. The camera is placed on the surface of the soil for 2.5 min, during which time data are collected every 4 s, giving as a final value the average value of the whole period. It is capable of measuring CO_2 flows at a range of 0 to 9.99 g CO_2 m^{-2} h^{-1}, with a precision of ± 1 SD and a resolution of 1 ppm. The principle on which the analyzer is based is a closed system in which the increases in the aerial CO_2 concentration found on the soil surface are calculated, for which quadratic equation fits are used.

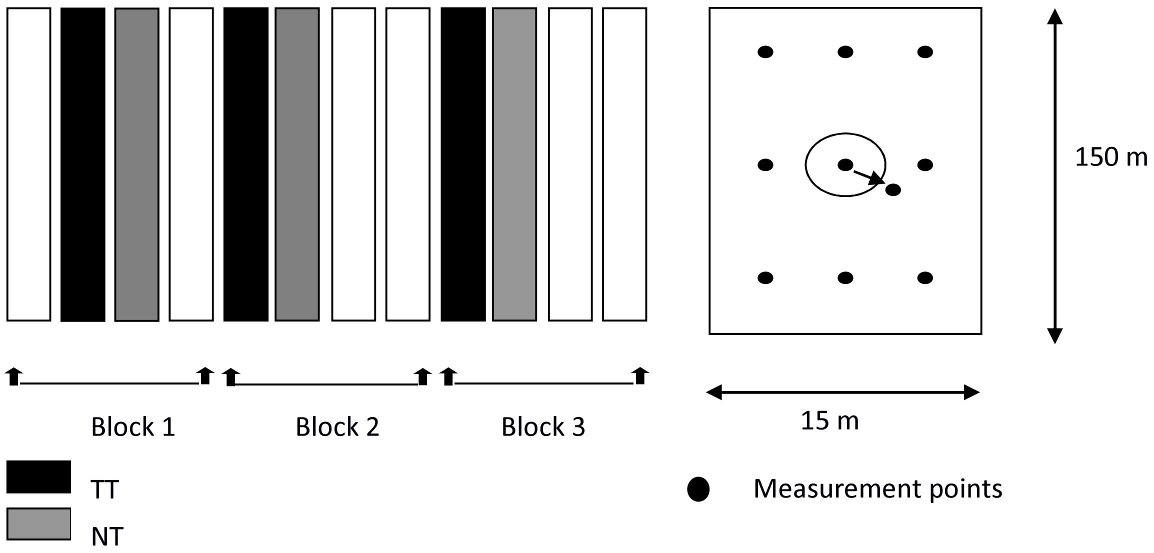


Figure IV-2. Diagram of the distribution in the Tomejil farm of the plots used for the field trials, and of an experiment unit with the sampling points indicated.

To observe the effects of the tillage operations used for the soil's preparation and sowing on gas emissions, measurements were made before these operations took place, immediately after them and at 2, 4, 6, 24 and 48 h after carrying them out in the two management systems considered in the study. Specific measurements were also made after the most important rain events to observe the effects of the increase in moisture in the soil on biological activity and the acceleration of decomposition of the residue.

IV-2.4. Data analysis

Analyses of variance (ANOVA) were used to detect the significance of the effect of the main factor: the tillage system. The separation of means was determined by a Tukey test, where the effects were statistically significant ($p<0.05$).

The fit of the regression models was made with the linear regression module in the program Statistix 8.

IV-3. RESULTS

Fig. IV-3a and b depicts the hourly evolution of the CO_2 emissions in both types of soil preparatory tillage operations for the farming season of 2006/07, in which pea was sown; Fig. IV-3c and d shows the emissions corresponding to the season of 2007/08, during which wheat was sown; Fig. IV-3e presents values for the season 2008/09, in which sunflower was sown; and Fig. IV-3f gives results for the season of 2009/10, in which pea was again sown. From these results, it can be observed that there were no notable differences in the gas emissions in areas subjected to the two management systems for the measurements taken prior to carrying out the preparatory work. However, immediately after performing the preparatory operations, the CO_2 emissions exhibited an important increase in the tilled soils compared to the measurements obtained in the non-tilled soils.

As can be observed in Fig. IV-3, the maximum CO_2 emission value for the different measurements corresponds to the period between 2 h and the 4 h following the tillage operations, and this is a common trend for both treatments as a result of the higher ambient temperature recorded at this time and the displacement of gas to non-tilled plots, which were very close to those of the traditional system. In the first measurement made on 14/11/06, it was noted that at 24 h, there was still a notable difference between the gas measured in both systems of cultivation, which led us to increase the measurement time in successive measurements until there were no significant differences in the emission values of either management system, fixing 48 h after the work in the soil was done as a measurement limit.

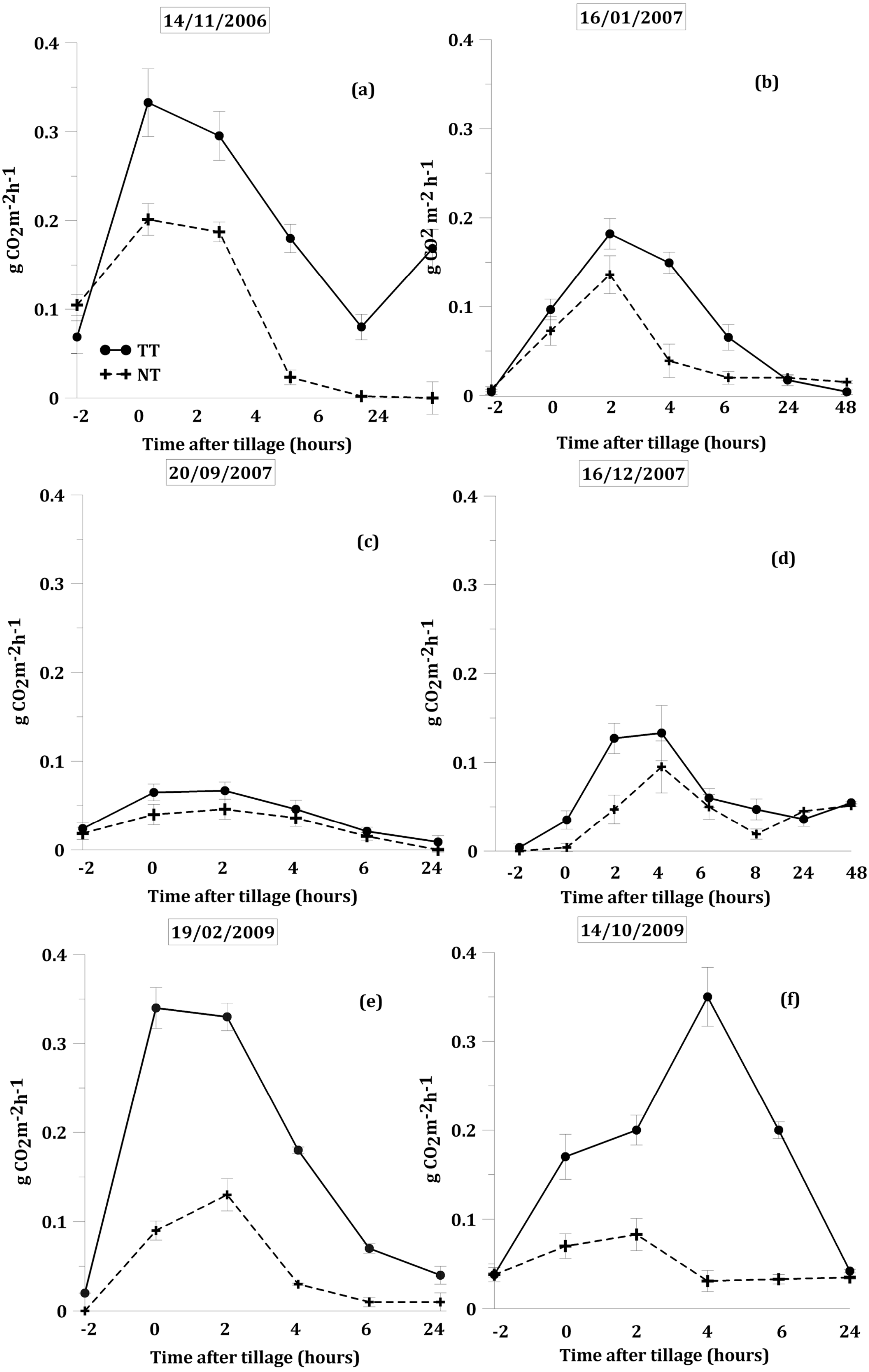


Figure IV-3. Hourly evolution of the CO_2 emissions during the preparatory tillage operations in the soil in both cultivation systems.

However, a comprehensive view of the behavior of the gas in the different measurements permits us to indicate that starting from the peak of the maximum emissions, the flux begins to decrease, until reaching similar values in both treatments at 24 h. The significant increase in CO_2 emissions that takes place immediately after tilling responds to the physical release of this gas trapped in the porous space of the soil.

Table IV-2 summarizes the daily emissions accumulated in both soil management systems and the moment at which the greatest differences in the gas flux that were recorded.

Table IV-2. Daily CO_2 emission values when performing tillage operations in soil and maximum differences in them between the two management systems.

Date	**Daily CO_2 emission kg ha^{-1}**		**Max. difference in emissions TT-NT**	**Max. T**	**Accumulated rainfall in the last month (mm)**	**Soil moisture (%)**
	TT	**NT**				
14/11/06	38.5	8.4	87% (4 hours)	21.2	127.8	20.5
16/01/06	20.3	8.5	74% (4 hours)	17.7	38.8	10.1
20/09/07	6.3	3.8	38.7% (opening)	34.2	11.0	2.9
16/12/07	13.7	9.1	63 % (2 hours)	16.0	66	11.36
19/02/09	22	6	73% (opening)	18.7	95.2	18.3
14/10/09	30	8	90% (4 hours)	31.3	44.6	10.6

At the points of maximum difference, higher carbon dioxide values on the order of between 39 and 90% were measured in the tilled soils compared to soils in which the profile had not been altered. Specifically, considering a period of 24 h, the soils under traditional management emitted 30.1 and 11.8 kg ha^{-1} more CO_2 than those managed under conservation agriculture conditions for the first and second tillage performed in the season of 2006/07, 2.5 and 4.6 kg ha^{-1} more for the tillage operations conducted in the second season, and 16 and 22 kg ha^{-1} for the seasons of 2008/09 and 2009/10, respectively.

Independent of the management system used, the highest CO_2 emission values were seen in the measurements made on 14/11/06 and 14/10/2009 due to the greater amount of moisture in the soil as a result of the rain accumulated in the month prior to the measurements being made; the lowest emissions were found in the measurement made on 20/09/07 due to the high temperatures recorded at that time, which conditioned the activity of the microorganisms in the soil that is responsible for decomposing organic remains.

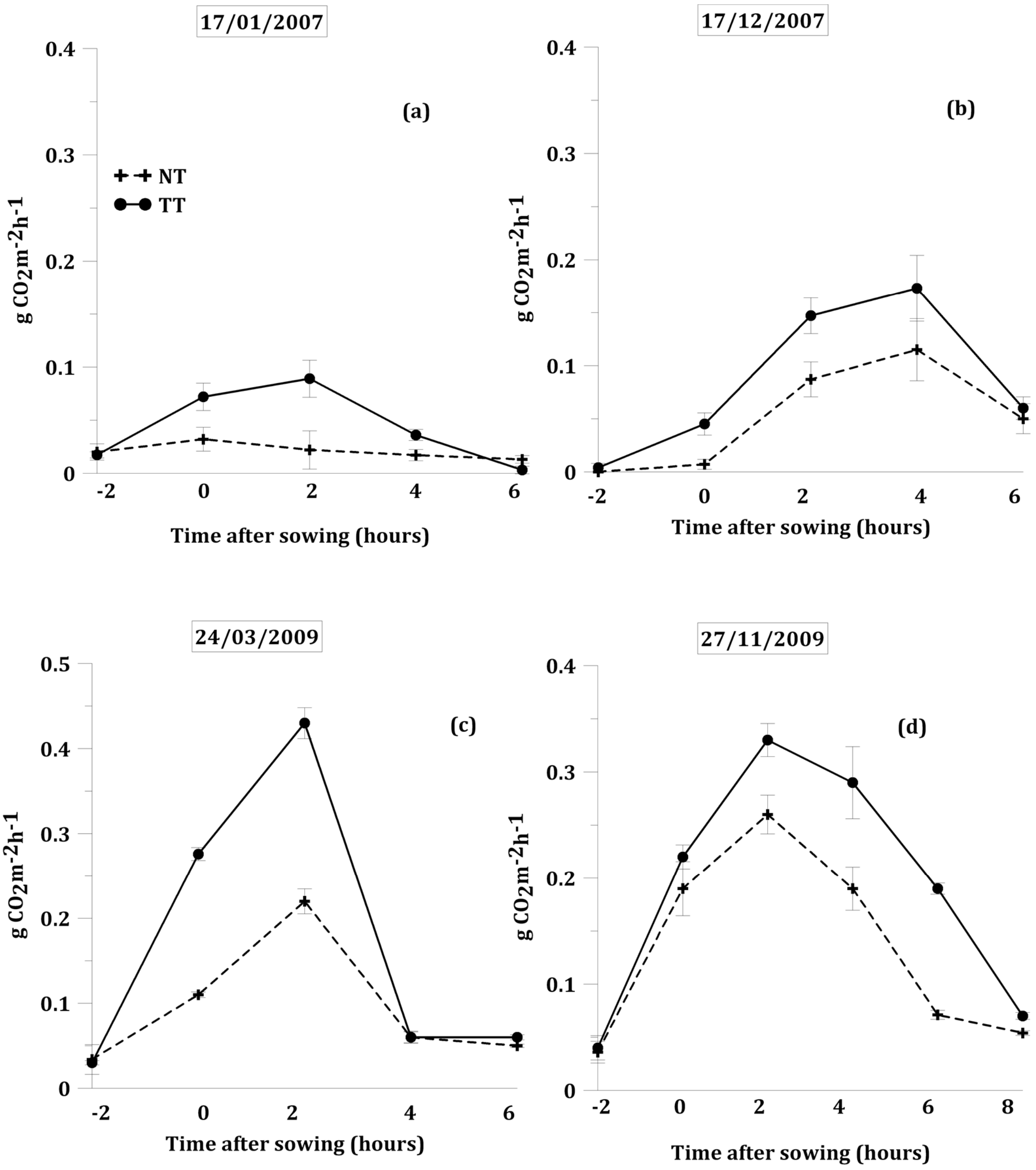


Figure IV-4. Hourly evolution of the CO_2 emissions during the sowing operations for the different farming seasons in both cultivation systems.

In the case of sowing (Fig. IV-4), the trend observed in the CO$_2$ flux was similar to that described for tillage, i.e., a maximum peak was noted between 2 and 4 h of the beginning the operations, and the highest values were estimated in the soils managed under the traditional system. However, due to the lesser depth of the alteration of the profile with sowing, at 6 h, the emission levels were similar in both management systems.

Table IV-3 summarizes the daily emissions accumulated on the sowing date and the moment at which the greatest differences in the CO$_2$ flux that were recorded between the management systems.

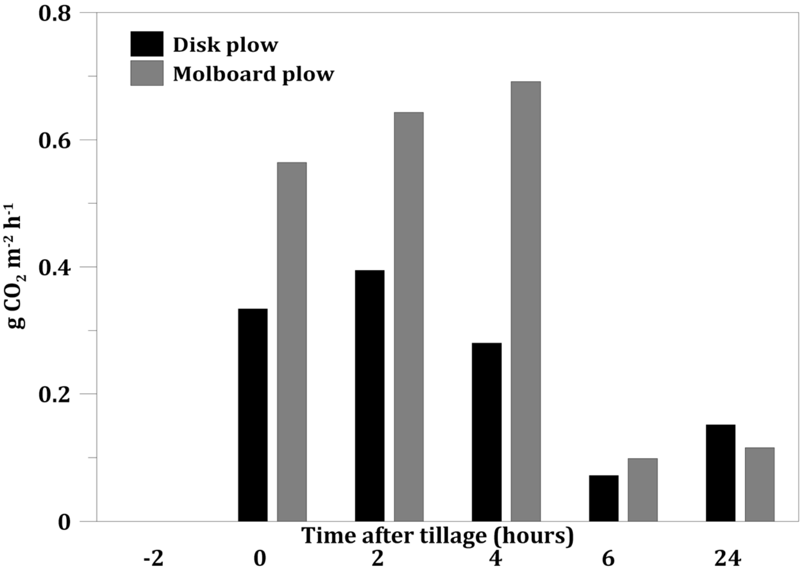
Table IV-3. Daily CO$_2$ emission values on the sowing dates and maximum differences in them between the two management systems.

Date of sowing	**Daily emission of CO$_2$ kg ha^{-1}**		**Max. Difference in emissions TT-NT**	**Max Temp**	**Rain accumulated in the last month (mm)**	**Soil moisture (%)**	**Days since preparatory tasks.**
	TT	**NT**					
17/01/07	8	3	75% (4 hours)	17	38.8	10.1	1
17/12/07	14.6	10	41% (4 hours)	15	66	11.36	1
24/03/09	23	5	49% (4 hours)	17	41.8	12.27	33
27/11/09	33	21	34.5% (4 horas)	16	6	3.4	44

With the aim of introducing a new variable that is of great importance in studying emissions, i.e., the depth of tillage, we proceeded to use a disk plow pass to till down to 20 cm of the profile, which has been the normal procedure used in the study plots devoted to traditional tillage. At the same time, a pass was made with a moldboard plow in some plots adjacent to the experimental plots, which reached up to a depth of 40 cm.

After the passes of the different machinery in the corresponding plots, the CO$_2$ emissions were measured in the same way as had been done throughout the field trials. The first reading was made before tillage, the following reading just after the pass, and the subsequent readings at 2, 4, 6, and 24 h, both in the plots in which the machinery passes were made and in those destined for no tillage, with the aim of comparing the three systems.

Fig. IV-5 shows the emission values at the different time points at which the CO_2 flux was measured and the difference between the values measured in the tilled soils compared to the no tillage sites.



No-tillage	**0 a**	**0.06 c***** 	**0.19 c*****	**0.14 c*****	**0.04 b****	**0.07 b****
Disk plow	**0 a**	**0.40 b*****	**0.59 b*****	**0.42 b*****	**0.11 a****	**0.22 a****
Molboard plow	**0 a**	**0.63 a*****	**0.83 a*****	**0.83 a*****	**0.14 a****	**0.18 a****

Figure IV-5. Increase in the hourly CO_2 emissions during the tillage operations in the soil in the different cultivation systems above the emissions measured in no tillage. Each value represents the mean of 14 readings.

As can be seen in the figure, the trend in the hourly gas emission is the same for the three cultivation systems and is dictated by the daily evolution of the temperature, which affects microbial activity.

Table IV-4 shows the increase in the emissions recorded in the plots subjected to any of the individual tillage systems expressed as the ratio of emissions in the tillage plots to those presented by the plots under no tillage.

As can be observed in Table IV-4, the ratio value in all of the tillage cases over the no-tillage cases was fairly high. In the cases of both the disk plow and the moldboard plow, the greatest difference was produced at the moment of the tillage pass, and the values were 6.7 and 10.5, higher than under no tillage, respectively.

Table IV-4. Increase of the gas emissions in each tillage system taking as reference unit the emissions in no tillage.

	Tillage	**2 hours after tillage**	**4 hours after tillage**	**6 hours after tillage**	**24 hours after tillage**
Disk Plow	6.7	3.1	3.0	2.7	3.1
Moldboard plow	10.5	4.4	6.0	3.5	2.6

Fig. IV-6 presents the CO_2 concentration in the air immediately after tillage was performed as a function of the amount of gas measured before the soil was tilled for both management systems and operations performed in the soil.

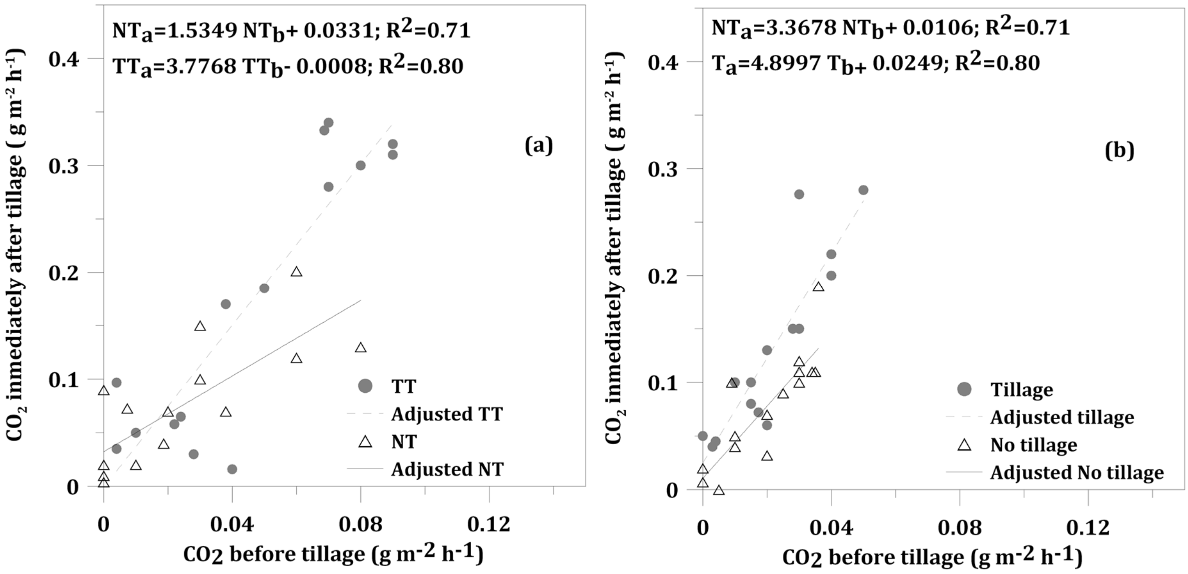


Figure IV-6. Relation of CO_2 flux before tillage and immediately after tillage, for both systems, traditional tillage (TT) and no- tillage (NT). (a) is for tillage operations; (b) is for sowing operations.

Lines are linear adjustments for tillage and no-tillage system. NTa and NTb are fluxes after and before tillage operations for tillage system. TTa and TTb are fluxes after and before tillage operations in no tillage system.

In Fig. IV-6, it can be seen how the increase observed after the tilling operations is linearly related to the flux measured before carrying out these operation, both for the preparatory work in the soil and the sowing operations. This indicates to us that the content of CO$_2$ in the soil conditions the emissions caused when any type of tillage is performed.

As can be seen in Table IV-3, in the case of conducting sowing where tillage operations had been conducted previously, the CO$_2$ levels retained in the soil were lower, so the emissions subsequent to the sowing operations presented lower emission fluxes, as they are linearly related.

IV-4. DISCUSSION

Reduced tillage is one of the most effective agricultural practices for reducing CO$_2$ emissions and for increasing the sequestration of atmospheric carbon in the soil (Sainju et al., 2008). Similarly, it has been observed that managing soil under a no-tillage system with residues left on the soil surface can further diminish the amount of emissions produced in comparison with the same type of system with bare soil (Al-Kaisi and Yin, 2008).

In the present study, the hourly emission values obtained (Fig. IV-3) are somewhat lower than those estimated by Álvaro et al. (2004) and by Morell et al. (2010) in the provinces of Zaragoza and Lleida, respectively, in northeastern Spain. The magnitude of the response of the conservation agriculture systems to the sequestration of carbon and to the reduction in emissions varied considerably depending on the depth of the work performed in the soil and the edaphic and climatic conditions of the area.

Climate notably modifies the nature and rapidity of the decomposition of plant remains and, thus, the carbon dioxide emitted into the atmosphere. Moisture and the temperature are among the most determinative variables (Brinson., 1977) because they influence both the growth of vegetation and microorganism activity, which are extremely vital factors in the formation of soils (see Table IV-2). Citing several publications, Kononova (1975) reached the conclusion that the maximum intensity of the decomposition of organic matter is observed under moderate temperature conditions (around 20 °C) and with a moisture content of approximately 60–80% of the maximum capacity to retain water. Increasing or reducing temperature and moisture simultaneously, beyond optimal levels, causes a decreased decomposition of organic matter, which results in an important reduction in the CO_2 emitted.

In our case (Table IV-3), the points of maximum difference all occurred at 4 h of sowing, and CO_2 values between 34 and 75% higher were measured in the tilled soils. The differences recorded throughout the investigated 24 hour period were that 5, 4.6, 18 and 12 kg ha^{-1} more emissions occurred in the soils that traditionally tilled compared to those subjected to conservation agriculture practices.

If these data (Table IV-3) are compared to those shown in Table IV-1, which correspond to the work done before sowing, it can be observed that the volumes of emissions for both management systems were somewhat lower in the latter. As mentioned previously, this was due to the lesser depth reached with sowing in comparison to the other type of operation. It should also be taken into account that sowing is often performed a short time after having conducted the previous operation in the soil to prepare the bed for sowing. This means that the volume of gas trapped in the soil is released with the first operation, and the short space of time remaining before sowing, in some cases only 1 day, does not permit large amounts of gas to be stored again. In Table IV-3, the lowest emission values are given for the sowing corresponding to 17/01/07 and 17/12/07, and they coincide in that in the two cases, a day had passed since the previous cultivator pass. In the other two cases, the period was increased to over 30 days, and the emission volumes were greater.

In research performed in the United States (Reicosky and Archer, 2007), the short-term effects of two management systems on CO_2 emissions, one of which used a moldboard plow, whereas the other used no tillage, were evaluated. These investigators detected higher emission rates, both at short and medium terms, for the tilled plots compared to those under no tillage. These emission values ranged from being 3.8 times higher than found under no tillage when the work was conducted closer to the surface (10 cm), up to emissions 10.3 times higher than those measured under no tillage in the case of deeper tillage (28 cm).

As can be observed in Fig. IV-5, in spite of the influence of temperature on the hourly gas emissions, highly significant differences can be seen among the three systems, with the highest emissions being produced in the plots tilled with the moldboard plow, followed by those tilled with the disk plow, and finally, as expected, in those with no tillage.

Based on a study in which different soil management systems were compared, Prior et al. (2000) suggested that the increase in CO_2 fluxes occurring after tillage passes was related to the depth of the operation and to the degree of the soil's alteration. This coincides with the results obtained given that, in the comparison of the two tillage systems, it was seen that the moldboard pass, which reached down to 40 cm, was associated with the highest emissions.

These results coincide with those obtained by Álvaro-Fuentes et al. (2007), who reached the conclusion that plots in which traditional tillage was performed with a moldboard plow presented the highest emission values. These authors also affirmed that the maximum emissions produced after tillage begin to diminish 3 h after the operation. In our case, this maximum was reached at 2, following which the emissions begin to progressively decrease.

The results obtained here show that managing soils using no tillage is an especially favorable technique to reduce the CO_2 fluxes emitted by these soils into the atmosphere compared to soils subjected to traditional management. This difference was seen to be increased in the emissions recorded after the work performed in the soil in the traditional tillage plots, which entails a breaking up of the aggregates in the soil and the release of the gas trapped in it. These increases were found to be over 80% higher in the tilled soils.

Climate conditions were observed to be of great importance in the flow of the emissions, with increases in the volume of emissions being detected when there was abundant rainfall in the month preceding the data taking being observed.

The depth of the tillage directly affected the amount of CO_2 emissions. Comparison between the disk plow and the moldboard plow permitted the quantification of a total of 18 kg ha^{-1} more gas emissions being produced from the soils tilled with the moldboard plow in the 6 h following carrying out tillage and 38 kg ha^{-1} more emissions if this operation is compared to no tillage.

It is also of interest to point out that by doubling the depth of the tillage, the amount of CO_2 emitted into the atmosphere is nearly doubled.

In Spain, where the emissions of greenhouse gasses (GHGs) greatly exceed the objectives fixed by the Kyoto protocol for the period 2008–2012, it is more necessary than ever to implement measures permitting us to fulfill those objectives. Therefore, in the agricultural sector, the adoption of Conservation Agriculture practices, especially no tillage management, could be a very important option for fixing atmospheric C in soils and reducing the emissions derived from agricultural operations.

IV-ACKNOWLEDGMENTS

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Chapter V.

Summary, resumen and general conclusions

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V-1. SUMMARY

Agriculture contributes to climate change, and is affected by it. On the one hand, solar energy is used primarily by photosynthetic organisms which transform it into carbohydrates, releasing oxygen (O_2) whilst consuming carbon dioxide (CO_2) and water. In inland areas, agriculture and forestry favor photosynthesis which is performed by plants and trees; that is how this chemical reaction that sustains life is generated. On the other hand, several agricultural activities, for example soil tillage and fertilization of crops, favor the emission into the atmosphere of greenhouse gases (GHG), such as CO_2 and nitrous oxide (N_2O). Therefore, the role of agriculture is twofold: as crops and trees consume some of the CO_2 in the atmosphere for photosynthetic reactions, and agricultural field tasks emit GHG. In other words, with regards to climate change, agriculture is part of the problem, but it is also part of the solution.

Currently, about 9% of total GHG emissions in the European Union come from agriculture, which is considered a net emitter of greenhouse gases. However, agriculture has an asset that no other productive sector may boast: the soil. There are various scientific studies that warn of the precarious situation of soils in areas where the intensification of agriculture has led to intensive tillage as a conventional practice to prepare the seedbed. In addition, there are numerous studies which confirm how, through conservation, agriculture soil quality is considerably improved, and that a sustainable use of soils can be achieved.

The term “sustainable” is used in almost all areas related to agriculture and the environment. It is a word not only appealing to non-specialists, but also for scientists and technicians in the field. The overuse of terms related to sustainability has produced misunderstandings, such as some specific benefits of particular agricultural systems being wrongly attributed to others. The scientific literature confirms that not all agricultural practices have an equal impact on the environment.

Therefore, it is necessary to correctly identify agricultural practices encompassed in the terms that they are used for. This thesis aims to clarify several questions related to conservation agriculture. For instance, in terms of soil conservation, minimum tillage or conventional tillage are not effective in reducing soil erosion, while no-tillage is a farming practice that significantly reduces it. Similarly, with respect to soil C sink effect, not all agricultural practices fix the same amount of C.

Global warming is a subject of international agreements, such as the Kyoto Protocol, where exceeding the amount of GHG emissions assigned to individual countries, would entail high economic fines. Not only is climate change a matter of unquestionable environmental concern, but it is also a budget issue for governments who have signed international agreements which address limits to GHG emissions. Of special importance is to correctly assign coefficients for C sequestration into the soil. Consequently, it is essential to know which agricultural practice we are referring to, as each practice is assigned a different C sequestration coefficient.

The objectives of this thesis are seeking to resolve these uncertainties. Firstly, new definitions of conservation agriculture practices are proposed, both for arable and perennial crops. In order to be broadly accepted, the definitions have been agreed with experts and stakeholders. Moreover, the definitions are in line with international trends, and are compared with other practices that can be interpreted as soil conservation. Secondly, coefficients of C sequestration have been developed for conservation practices for both perennial crops and arable crops. And finally, field work evaluating CO_2 emissions which are associated with conservation practices, compared to conventional tilling-based ones, was performed in the Andalusian countryside (Spain).

Chapter I introduces the current situation with regards to agriculture and climate change. Given that 14 out of 15 of the hottest years on record have been in the 21st Century, and GHG emissions are continuously growing, actions are most needed in all economic sectors to mitigate and adapt to global warming. Without a doubt, agriculture is no exception.

In Chapter II of this thesis, a new vision of conservation agriculture is addressed. Within this farming system, no-tillage is considered the best practice for arable crops whereas groundcovers is the best approach for perennial crops. Reduced tillage or minimum tillage is not recommended in practical terms as a valid option within conservation agriculture, given that only in very exceptional circumstances, more than 30% of plant debris remains after sowing.

Coefficients of C sequestration that are assigned to each practice (tillage, reduced tillage and groundcovers) are addressed in Chapter III. Since the behaviour of the soil is different in relation to C sequestration, two periods of study have been differentiated: 1-10 years and more than 10 years. According to the results of the studies reviewed, it can be concluded that the empirical data confirm the suitability of the selection of practices included in Chapter II. Indeed, while in no-tillage and groundcovers coefficients of C sequestration are always positive, regardless of the length of time farmers have been following those conservation agriculture practices, in the case of reduced tillage an initial depletion of C on the soil can be expected.

The C sequestration coefficient for no-tillage is 0.85 Mg C ha^{-1} year^{-1} from 1 to 10 years, while in the same period, in the case of reduced tillage a loss of -0.16 Mg C ha^{-1} year^{-1} can be expected. In the case of perennial crops, in the first 10 years, the absorption coefficient is 1.54 Mg C ha^{-1} year^{-1}. After 10 years, lower coefficients for C sequestration are found. In the case of no-tillage (0.16 to 0.40 Mg C ha^{-1} year^{-1}) and groundcover (0.35 Mg C ha^{-1} year^{-1}). In contrary to the first period for reduced tillage, a positive C sequestration is estimated after 10 years (0.03 to 0.30 Mg C ha^{-1} year^{-1}).

In Chapter II, adoption of both no-tillage and groundcovers in Spain is assessed. At the time of writing this summary of the thesis, there is another year of official estimates. By 2014, no-tillage is assessed at 590,472 ha, whereas groundcovers reach 1,259,079 ha.

Consequently, by performing the calculations with the C sequestration coefficients previously proposed, the sequestration potential in Spanish soils would be up to

2,441 Gg C year^{-1}using current adoption figures. However, this amount could be much higher. For instance, most arable crops (cereals, legumes, and forage plants) and perennial crops (olive, fruit groves and vineyard) are suitable for conservation agriculture. In 2014, those crops sum up 12.7 M ha for arable and perennial crops, 7.8 M ha and 4.9 M ha respectively. Therefore, if most crops migrated to conservation agriculture, the annual C sequestration potential would be up to 14,168 Gg C year^{-1}.However, international agreements refer to CO_2 and not C. The relationship between the molecular weights of CO_2 (44 g) and C (12 g). Therefore, multiplying the previous figure 14,168 Gg C year^{-1} by 44 and dividing by 12, we obtain 51,950 Gg CO_2 year^{-1}.

So as to put this CO_2 sequestration potential into the context of the Kyoto protocol, Spain's GHG emissions in the period 2008-2012 reached 1,822,692 Gg CO_2, of which 10,7% correspond to the agricultural sector (195,028 Gg CO_2).Instead, the CO_2 amount permitted to be in line with the Kyoto Protocol in the period 2008-2012 was 1,657,110 Gg CO_2.Therefore, in the period 2008-2012 Spain issued an excess in emissions of 165,582 Gg CO_2. This represents a 26.5% increase, exceeding the 15% permitted by Spain in the Kyoto Protocol. Spain has solved the excess emissions problem by buying other countries' emissions quotas.

Actually, countries with commitments under the Kyoto Protocol (Annex B Parties) accepted targets for limiting or reducing emissions. These targets are expressed as levels of allowed emissions, or "assigned amounts," over the 2008-2012 commitment period. The allowed emissions are divided into "assigned amount units". In addition, emissions trading, as set out in Article 17 of the Kyoto Protocol, allows countries which have emission units to spare -emissions permitted by them but not "used"- to sell this excess capacity to countries over their limits. To compensate for the excess emissions of 165,582 Gg CO_2, Spain paid a sum of € 812 M at the international emissions trade. That represents an average unit price of approximately 4.90 €/Mg.

Coming back to the CO_2 sequestration potential of conservation agriculture, it would account for 259,752 Gg CO_2 in the period 2008-2012, which comes from an annual sequestration rate of 51,950 Gg CO_2 multiplied by 5 years. That would mean that 14.25% of total emissions, 133.19% of the agricultural sector releases, and 156.87% of the excess emissions of Spain in that period, could have been compensated for by employing conservation agriculture.

In economic terms, according to the coefficients for C sequestration addressed by conservation agriculture and the 2014 year figures of conservation agriculture in the country, the Spanish Government could have saved almost € 219M in international emissions trade for the 2008-2012 period. Moreover, if conservation agriculture were to be fully implemented in the main arable and perennial crops, that figure could rise to € 1,273 M.

The results that assess the influence of each soil management system are presented in Chapter III in relation to CO_2 emission data associated to different soil management systems. According to previous studies, it is known that CO_2 emissions are related to the temperature and soil humidity. The most favorable conditions for these emissions to occur are moderate temperatures around 20ºC, and a moisture content of around 60-80% of the maximum water holding capacity of the soil.

The study was conducted during 3 agricultural campaigns in the South of Spain, in a typical vertisol of the Andalusian countryside. In each season, typical conventional tillage field task emissions were compared to no-tillage, where no soil work was performed. In addition, emissions were compared during the tasks of sowing in both systems. The conditions of temperature and moisture varied during the seasons when taking measurements, and although temperature measurements in the planting tasks was near the optimum value of 20ºC (15ºC-17ºC) in the preparatory work, a peak was reached of 34.2ºC. However tasks were performed at the usual time in the area, so the results are faithful to what happens in the field. The deeper soil profile was tilled, the higher CO_2 emissions were recorded. The disc harrow penetrated into the work about 20 cm, while the moldboard about 40 cm. With reference to the emissions in no-tillage, disc harrow increased emissions at the time of performing the work6.7 times the no-tillage benchmark, while the plow, 10.5 times.

In conclusion, conservation agriculture is a remarkable improvement in terms, not only of C sequestration, but also of less CO_2 emissions into the atmosphere. It is therefore an agricultural system that should be strongly encouraged within the policies aimed at mitigating and adapting to climate change. Not only should conservation agriculture be supported for environmental reasons, but also for the high economic savings it may well promote for national budgets related to climate change.

V-2. RESUMEN

La agricultura contribuye al cambio climático y se ve afectada por él. La energía solar es utilizada en primer lugar por los organismos fotosintéticos que la transforman consumiendo dióxido de carbono (CO_2) y agua, liberando oxígeno (O_2) y generando hidratos de carbono. En las zonas continentales, gracias a la agricultura y la silvicultura, mediante la fotosíntesis que realizan las plantas y árboles se genera esta reacción química que sustenta la vida. Por otra parte, diversas actividades agrícolas, como el laboreo del suelo y la fertilización de los cultivos, favorecen la emisión a la atmósfera de gases de efecto invernadero como el CO_2 y el óxido nitroso (N_2O). Por tanto, en el sector agrario se presenta la doble vertiente de, por un lado, consumir parte del CO_2 presente en la atmosfera para las reacciones fotosintéticas, y por otro lado, emitir también gases de efecto invernadero debido a las tareas propias del ámbito agrario. En otras palabras, la agricultura es parte del problema pero también parte de la solución al reto del cambio climático.

Actualmente, alrededor del 9% del total de las emisiones de gases de efecto invernadero de la UE provienen de la agricultura, por lo que se considera un sector emisor neto de gases de efecto invernadero. No obstante, la agricultura tiene un activo que ningún otro sector productivo posee: el suelo. No son pocos los estudios científicos que alertan de la precaria situación de los suelos en zonas donde la intensificación de la agricultura ha conllevado el laboreo intensivo como práctica convencional. Afortunadamente, no son pocos los estudios que confirman cómo a través de la agricultura de conservación se mejora sensiblemente la calidad de los suelos y se puede alcanzar un uso sostenible de los mismos.

El término “sostenible” se usa en casi todos los ámbitos relativos a agricultura y medio ambiente. Es una palabra apetecible no solo para no especialistas en la materia, sino también para científicos y técnicos. La literatura científica corrobora que no todas las prácticas agrarias impactan de igual forma el medio ambiente. Es por ello que es necesario identificar correctamente las prácticas agrarias englobadas en los términos que se empleen, por ejemplo agricultura de conservación, puesto que el citado sobreuso del término ha provocado que sea relativamente frecuente leer documentos donde se atribuyen beneficios inherentes de unos sistemas agrarios a otros. En términos de conservación de suelos, el mínimo laboreo o el laboreo convencional no son eficaces a la hora de reducir la erosión, mientras que la siembra directa es una práctica agraria que la reduce sensiblemente. De igual manera, con respecto al efecto sumidero de C que tiene el suelo, no todas las prácticas fijan la misma cantidad de C.

El calentamiento global es objeto de acuerdos a escala global, como el protocolo de Kioto, donde se asignaban cantidades de emisiones de gases de efecto invernadero a países, que de verse excedidas, supondrían elevados costes económicos. El cambio climático es por tanto un asunto de indudable interés ambiental, pero también presupuestario para los gobiernos que han suscritos acuerdos internacionales que conllevan limitación de emisiones. Por tanto, es de especial importancia asignar correctamente coeficientes relativos a captura de C en el suelo. Se debe identificar a qué práctica agraria nos referimos, dado que los coeficientes son diferentes y dependen de la práctica agraria realizada.

Los objetivos planteados en esta tesis buscan solventar estas incertidumbres. En primer lugar, se proponen nuevas definiciones de las prácticas de agricultura de conservación, tanto a los cultivos herbáceos y perennes. Con el fin de ser ampliamente aceptadas, las definiciones se han acordado con los expertos y las partes interesadas. Por otra parte, las definiciones están de acuerdo con las tendencias internacionales, y se comparan con otras prácticas que pueden ser interpretadas como la conservación del suelo. En segundo lugar, se han desarrollado coeficientes de captura de C para las prácticas de conservación, tanto para cultivos perennes como para cultivos herbáceos. Y por último, se ha realizado un trabajo de campo donde se han evaluado las emisiones de CO_2 que se asocian a las prácticas de conservación con respecto a la agricultura convencional, basada en el laboreo de los suelos, en una experiencia de campo en la campiña andaluza.

El Capítulo I presenta la situación actual con respecto a la agricultura y el cambio climático. Teniendo en cuenta que 14 de los 15 años más cálidos desde que existen registros han sido en el s.XXI, y las emisiones de gases de efecto invernadero crecen de forma continuada, es necesario implementar medidas en todos los sectores económicos para mitigar y adaptarse al calentamiento global. Y la agricultura no es una excepción.

En el Capítulo II de esta tesis es donde se aborda la nueva visión de la agricultura de conservación. Dentro de este sistema agrario se consideran como prácticas adecuadas la siembra directa para cultivos extensivos y las cubiertas vegetales para cultivos leñosos. El tan comúnmente empleado término de laboreo reducido o laboreo mínimo se excluye en términos prácticos de la agricultura de conservación, dado que solo en condiciones muy excepcionales permanecen más del 30% de restos vegetales tras la siembra.

Los coeficientes de fijación de C que se le asignan a cada práctica (siembra directa, laboreo reducido y cubiertas vegetales), se recogen en el Capítulo III. Dado que el comportamiento del suelo es diferente en relación a la fijación de C, en función del tiempo que se lleven realizando prácticas de conservación, se han diferenciado dos periodos de estudio: experiencias de menos de 10 años en agricultura de conservación o de más de 10 años. A tenor de los resultados de los estudios revisados, se puede concluir que los datos empíricos refrendan la idoneidad de la selección de prácticas englobadas en la agricultura de conservación del Capítulo II. En efecto, mientras que en la siembra directa y las cubiertas vegetales los coeficientes de fijación de C al suelo son siempre positivos, independientemente de los años que se lleven realizando las prácticas de conservación, en el laboreo reducido se puede tener un empobrecimiento inicial de C en el suelo.

El coeficiente para la siembra directa es de 0,85 Mg C ha^{-1} $año^{-1}$ hasta los 10 años, mientras que en ese mismo periodo, en el caso del laboreo reducido se puede esperar una pérdida de -0,16 Mg C ha^{-1} $año^{-1}$. En el caso de los cultivos leñosos, en los 10 primeros años, el coeficiente de absorción de C es de 1,54 Mg C ha^{-1} $año^{-1}$. A partir de los 10 años de estar empleando estas técnicas los coeficientes bajan en el caso de la siembra directa (0,16-0,40 Mg C ha^{-1} $año^{-1}$) y cubiertas vegetales (0,35 Mg C ha^{-1} $año^{-1}$) y es de esperar que en este periodo sí aumenten en el caso del laboreo reducido (0,03-0,30 Mg C ha^{-1} $año^{-1}$).

En el Capítulo II también se valora la adopción de la siembra directa y las cubiertas vegetales en España. En el momento de escribir este capítulo de la tesis, existe otro año de estimaciones oficiales de la adopción de técnicas de agricultura de conservación con respecto a lo publicado en el artículo que comprende dicho capítulo. En concreto, para el año 2014, la siembra directa se estima en 590.472 ha, mientras que las cubiertas vegetales suman 1.259.079 ha.

Por lo tanto, el potencial de secuestro en suelos de España sería 2.441 Gg C $año^{-1}$ con las cifras de 2014. No obstante, este potencial podría ser mucho mayor. Por ejemplo, los cultivos herbáceos (incluyendo cereales, legumbres y plantas forrajeras) y cultivos leñosos (olivos, frutales y viñedos) son aptos para la agricultura de conservación. Esos cultivos se extienden por 12,7 M ha en total. Los cultivos herbáceos abarcan 7,8 M ha y los leñosos 4,9 M ha. Por lo tanto, si la mayoría de los cultivos migraran a agricultura de conservación, el potencial anual de captura de C podría ser de hasta 14.168 Gg C $año^{-1}$. No obstante, en los acuerdos internacionales las cifras se refieren a CO_2 en vez de C. La relación entre los pesos moleculares del CO_2 (44 g) y el C (12g). Por tanto, multiplicando la cifra anterior 14.168 Gg C $año^{-1}$ por 44 y dividiendo por 12, nos resultan 51.950 Gg CO_2 $año^{-1}$.

Poniendo estas cifras en el contexto del protocolo de Kioto, las emisiones de gases de efecto invernadero de España en el período 2008-2012 alcanzaron 1.822.692 Gg

CO_2, de las que el 11,1% se debieron al sector agrario (195.028 Gg CO_2). La cantidad de emisiones CO_2 permitidas para cumplir con el Protocolo de Kioto en el período 2008-2012 eran de 1.657.110 Gg CO_2. Por lo tanto, en dicho período España emitió un exceso de 165.582 Gg CO_2. Esto representa un aumento del 26,5%, superando el 15% permitido a España en el Protocolo de Kioto. España ha resuelto las sobre emisiones mediante la compra de las derechos de otros países.

Los países con compromisos del Protocolo de Kioto (Anexo B Partes) aceptaron objetivos para limitar o reducir las emisiones. Estos objetivos se expresan como niveles de emisiones permitidas, o "cantidades asignadas", durante el período de compromiso 2008-2012. Las emisiones permitidas se dividen en "unidades de cantidad atribuida". Además, el comercio de emisiones, tal como se establece en el artículo 17 del Protocolo de Kioto, permite a los países que cuentan con unidades de emisión sobrantes –emisiones que no llegan a realizar- vender este exceso de capacidad a los países que están por encima de sus objetivos. Para compensar esas mayores emisiones de 165.582 Gg CO_2, España compró en el comercio internacional de emisiones por un importe de 812 M €. Eso representa un precio promedio de alrededor de 4,90 €/Mg.

El potencial de secuestro de CO_2 de la agricultura de conservación explicaría 259.750 Gg CO_2 en el periodo 2008-2012, resultante de multiplicar las emisiones anuales de 51.950 Gg CO_2 año^{-1} por los cinco años englobados en ese periodo. Eso significaría que el 14,25% de las emisiones totales, 133,19% de los del sector agrícola, y el 156,87% de las emisiones de más de España en el dicho período, se podría haber compensado a través de la agricultura de conservación.

En términos económicos, aplicando los coeficientes de secuestro de C asignados a la agricultura de conservación a las superficies en agricultura de conservación en España del año 2014, el Gobierno de España se podría haber ahorrado en el periodo 2008-2012 casi 219 M € en el mercado internacional de emisiones. Además, si se aplicasen esos coeficientes al total de hectáreas potenciales que podrían estar en agricultura de conservación, esa cifra podría subir hasta los 1.273 M €.

En relación a los datos de emisión de CO_2 asociados a diferentes sistemas de manejo de suelo, en el Capítulo III se recogen los resultados que evalúan la influencia del sistema de laboreo seguido. De acuerdo a trabajos previos, se sabe que las emisiones de CO_2 están relacionadas con la temperatura y la humedad que tenga el suelo. Las condiciones más favorables para que se produzcan estas emisiones son unas temperaturas moderadas, alrededor de 20ºC, y un contenido de humedad en torno al 60-80% de la máxima capacidad de retención del suelo.

El estudio se realizó durante 3 campañas agrícolas en el sur de España, en un vertisol típico de la campiña andaluza. Durante cada campaña, se compararon las tareas de preparación de suelo típicas del laboreo convencional de la zona, con la siembra directa, donde no se realizaba labor alguna. Además, se compararon las emisiones durante las tareas de siembras en ambos sistemas. Las condiciones de temperatura y humedad variaron a lo largo de las campañas a la hora de tomar las mediciones, y si bien en temperatura en las mediciones realizadas en las tareas siembra se estaba cerca del valor óptimo de 20ºC (15ºC-17ºC), en las labores preparatorias se alcanzaron picos de 34,2ºC. No obstante las tareas se realizaron en la época habitual de la zona, por lo que los resultados son fieles a lo que ocurre en campo. A mayor profundidad del perfil de suelo labrado, mayor es la emisión de CO_2 que se registra. La grada de discos profundiza en la labor unos 20 cm, mientras que la vertedera unos 40 cm. Tomando como referencia las emisiones registradas en la siembra directa, la grada de discos aumentó en el momento de realizar la labor 6,7 veces la cifra de referencia, mientras que la labor de vertedera 10,5.

En resumen, la agricultura de conservación supone una notable mejora en términos, no sólo de captura, sino también de reducción emisiones de CO_2 a la atmósfera. Es por tanto un sistema agrario que se debe potenciar de manera intensa en las medidas que busquen la mitigación y adaptación al cambio climático. No sólo se debería apoyar la agricultura de conservación por razones ambientales, sino también para los altos ahorros económicos que bien puede promover para los presupuestos nacionales relacionados con el cambio climático.

V-3. GENERAL CONCLUSIONS

1. Conservation agriculture is a system that is well adapted to Mediterranean conditions. Its environmental benefits include control of erosion, increased soil organic matter, less soil compaction, reduced CO_2 emissions, improved biodiversity, and lower risk of potential contamination of the water. The adoption of conservation agriculture in Spain shows a positive trend, being performed by 7.8% of the arable and 25.6% of perennial crops.

2. As a result of the working sessions organized with experts in the framework of this thesis, the tentative proposals have resulted in agreed definitions of conservation agriculture. This has made it possible to clarify which practices are most suitable for conservation agriculture in Mediterranean conditions. The definitions have been agreed in Spain, but can be extrapolated to other countries with Mediterranean climate. This clearer situation may help governmental bodies to design specific schemes related to climate change and the agri-environment aiming at the uptake of conservation agriculture in the area.

3. No-tillage is acknowledged as the best practice for arable crops, while groundcovers are the best approach for perennial crops. Although reduced tillage is sometimes acceptable as a conservation tillage practice for arable crops, it is not considered adequate for conservation agriculture. In Mediterranean areas, seldom more than 30% of residues of the previous crop are present after seeding.

4. Conservation agriculture implementation could help meet the targets set in the international agreements related to climate change, such as the Kyoto Protocol. According to official statistics and the carbon sequestration coefficients calculated in this thesis, Spain would have saved around € 219 M in the period 2008-2012. In addition, if conservation agriculture were to be fully implemented in the main arable and perennial crops, that figure could rise to € 1,273 M.

5. The potential for carbon sequestration in conservation agriculture is not constant over time. Thus, in newly implemented fields, carbon sequestration rates are high during the first 10 years, followed by a period of lower but steady growth to reach an equilibrated rate.

6. Crop rotations present higher values of carbon sequestration coefficients than monocultures in arable crops. In perennial crops, native cover crop species lead to higher values of carbon sequestration coefficients than sowed species.

7. Based on the results of this thesis, it can be stated that agricultural policies that promote a shift to farming systems enhancing carbon content in soils, such as conservation agriculture, are considered more relevant than those policies focused on the reduction of CO_2 emissions. The mitigation effect of the reduced emissions is small compared to the amount of carbon that can be stored in soils.

V-4. ACKNOWLEDGEMENTS

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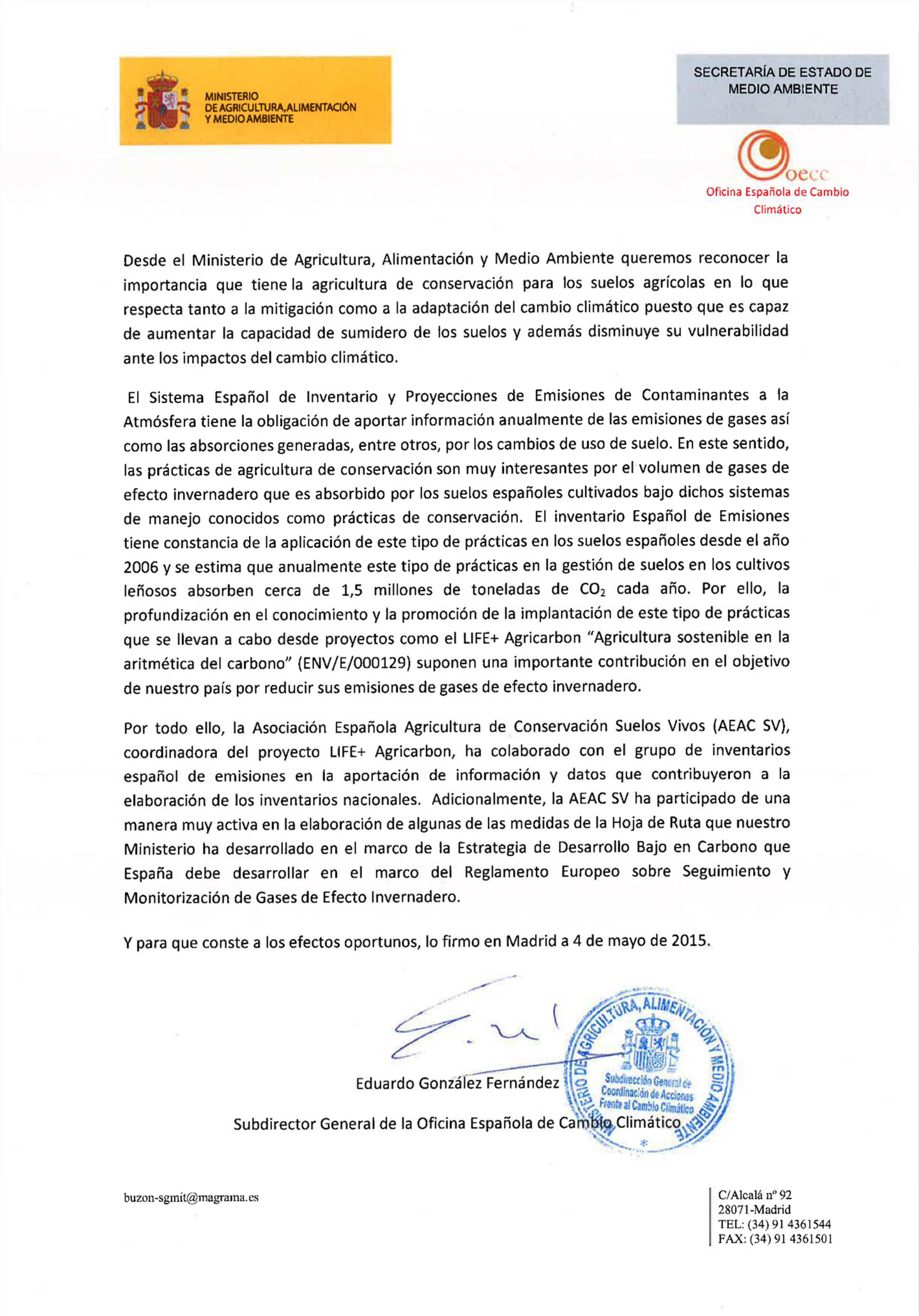
Annex I.

Letter from the Spanish Office for Climate Change. Ministry for Agriculture, Food and Environment, Spain.



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Oficina Española de Cambio
Climático

Desde el Ministerio de Agricultura, Alimentación y Medio Ambiente queremos reconocer la importancia que tiene la agricultura de conservación para los suelos agrícolas en lo que respecta tanto a la mitigación como a la adaptación del cambio climático puesto que es capaz de aumentar la capacidad de sumidero de los suelos y además disminuye su vulnerabilidad ante los impactos del cambio climático.

El Sistema Español de Inventario y Proyecciones de Emisiones de Contaminantes a la Atmósfera tiene la obligación de aportar información anualmente de las emisiones de gases así como las absorciones generadas, entre otros, por los cambios de uso de suelo. En este sentido, las prácticas de agricultura de conservación son muy interesantes por el volumen de gases de efecto invernadero que es absorbido por los suelos españoles cultivados bajo dichos sistemas de manejo conocidos como prácticas de conservación. El inventario Español de Emisiones tiene constancia de la aplicación de este tipo de prácticas en los suelos españoles desde el año 2006 y se estima que anualmente este tipo de prácticas en la gestión de suelos en los cultivos leñosos absorben cerca de 1,5 millones de toneladas de CO_2 cada año. Por ello, la profundización en el conocimiento y la promoción de la implantación de este tipo de prácticas que se llevan a cabo desde proyectos como el LIFE+ Agricarbon "Agricultura sostenible en la aritmética del carbono" (ENV/E/000129) suponen una importante contribución en el objetivo de nuestro país por reducir sus emisiones de gases de efecto invernadero.

Por todo ello, la Asociación Española Agricultura de Conservación Suelos Vivos (AEAC SV), coordinadora del proyecto LIFE+ Agricarbon, ha colaborado con el grupo de inventarios español de emisiones en la aportación de información y datos que contribuyeron a la elaboración de los inventarios nacionales. Adicionalmente, la AEAC SV ha participado de una manera muy activa en la elaboración de algunas de las medidas de la Hoja de Ruta que nuestro Ministerio ha desarrollado en el marco de la Estrategia de Desarrollo Bajo en Carbono que España debe desarrollar en el marco del Reglamento Europeo sobre Seguimiento y Monitorización de Gases de Efecto Invernadero.

Y para que conste a los efectos oportunos, lo firmo en Madrid a 4 de mayo de 2015.

Subdirección General de Coordinación de Acciones Frente al Cambio Climático

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Annex II.

XVII Andalucía Environment Award to the LIFE+ Agricarbon project. Government of Andalusia, Spain.

XVII PREMIOS ANDALUCÍA DE MEDIO AMBIENTE

Reunido en Sevilla el Jurado de los
Premios Andalucía de Medio Ambiente
en su XVII Convocatoria
acuerda conceder el premio en la modalidad de

"Mejor Proyecto Contra el Cambio Climático" a la
Asociación Española Agricultura de Conservación Suelos Vivos

El Presidente

El Secretario

JUNTA DE ANDALUCIA
CONSEJERÍA DE AGRICULTURA, PESCA Y MEDIO AMBIENTE

Annex III.

VII Congress on Agri-engineering Award as the best presentation at the session on Sustainable Production.

INNOVAR y PRODUCIR para el FUTURO

SEAgIng
SECH

VII CONGRESO IBÉRICO DE AGROINGENIERÍA Y CIENCIAS HORTÍCOLAS
Madrid, 26-29 Agosto 2013

Dña Eva Cristina Correa Hernando, Secretaria General del Comité Organizador del VII Congreso Ibérico de Agroingeniería y Ciencias Hortícolas

CERTIFICA

Que la comunicación oral titulada **Agricultura sostenible en la aritmética del carbono**, cuyos autores son *Emilio Jesús González Sánchez; Jesús A. Gil Ribes; Rafaela Ordóñez Fernández; Juan Agüera Vega; Francisco Márquez García; Oscar Veroz González; Manuel Gómez Ariza; Rosa Carbonell Bojollo; Gregorio L. Blanco Roldán; Sergio Castro García; Paula Triviño Tarradas* ha obtenido el premio al mejor trabajo presentado en la sesión de **Producción sostenible y agricultura ecológica** en el **VII Congreso Ibérico de Agroingeniería y Ciencias Hortícolas**, celebrado en Madrid los días 26, 27, 28 y 29 de agosto de 2013.

Y para que conste a los efectos oportunos, firma la presente en Madrid a 28 de agosto de 2013

Dña. Eva Cristina Correa Hernando